RCA III
Effects of Sediment on the Aquatic Environment: Potential NRCS Actions to Improve Aquatic Habitat

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Introduction

The issue of sediment in aquatic environments has been a topic of concern for many decades. During the nineteen-thirties, erosion became a national issue because of the dust bowl and as a result the Soil Erosion Service was established. Since the nineteen-thirties, the study of sediment erosion, transport, deposition, and intrusion has increased exponentially in the United States. Considering all of the past and current research, it is difficult to focus on essential research, but with limited resources it is imperative to refine the topics and prioritize the necessary areas of study. The same scoping is also true for treatment practices. The best and most effective treatment should be used on the most critical habitat. Establishing this systematic prioritization is a challenging but substantive endeavor.

Historical Perspective

One of the first well-distributed articles published was written by M.M. Ellis in 1936. Ellis covered many aspects of the effects of silt in aquatic systems, including light penetration, temperature adjustment, electrolytes, bottom conditions, and retention of organic matter. For sediment intrusion into streambeds, Ellis (1936) reported, from experimental data, very high mortality rates for freshwater mussels living in gravel-bedded or sand-bedded channels. These findings have been empirically supported by hundreds of subsequent studies. Only one study, written by Ward (1938a, 1938b), has refuted the effects of fine sediment on the health of aquatic ecosystems and this study has been heavily criticized in subsequent studies.

A substantiating study was conducted in 1943 by Shaw and Maga; this study investigated the effects of silt on the survival of salmon fry. The experiment was conducted in a flume with control groups. Salmon eggs were placed in nests and mining silt was introduced into the water supply periodically. Their results showed an average decrease of 64 percent in survival rates with a range of 80 percent to 16 percent. Subsequent studies were modeled after this laboratory experiment with very similar results.

The nineteen-fifties brought more experiments on survival rates. Land-use effects were being considered with an emphasis on logging. That approach refined previous knowledge but did not propose treatments for excess sediment in aquatic systems. Logging was still relatively unrestricted and economic concerns were a priority over the environment.

The nineteen-sixties resulted in more research and the idea of watershed management related to aquatic health was extensively explored. Many pioneers in the field -- such as McNeil, Shapely, Phillips, Platts, Bjornn, and others -- were establishing themselves as the experts. Since there is now such a large volume of material available, this paper will emphasize the review of theories, concepts, and established practices that are representative of the field as a whole. This methodology, although expedient, will most certainly leave out some pertinent information and practices. The attached bibliography (Appendix: The Effects of Fine Sediment on Aquatic Habitat: A Comprehensive Bibliography) should be consulted as a more thorough representation of where this field of study has gone and is going.

A trend which is apparent in the literature, when it is reviewed chronologically, is that of scale. Older studies (pre-1950) have more of a watershed or system approach. As studies progressed through the decades the system emphasis was lost to specialized studies for very specific areas. Specialized studies are important because they provide quantitative data, but it is important to relate this information to the larger system, whether it is a stream, watershed, or continent.

System Complexity

There are many problems associated with sediment in the aquatic environment and difficulties with the study of aquatic systems. They are complex interactive systems. Isolation of sedimentation effects on an aquatic system has not been effectively accomplished and is probably not a reasonable expectation for research in a natural interactive and responsive system. Many studies have been conducted in laboratories, but questions can be raised as to their applicability to natural systems.

Many laboratory studies of sediment intrusion have used mono-modal or simplified gravel mixtures. Some researchers have determined that a certain size class (often d50 or d84) is the most representative or critical of the particle size distribution. This leads to experiments utilizing mono-modal sizes and eliminates mitigating or aggravating factors that are not accounted for in the laboratory (Everest et al. 1987). Mitigating factors may be a local increase in velocity or shear stress to offset an increase in sediment input, while aggravating factors would be a decrease in velocity or shear stress.

Another important limitation is combined or cumulative effects. Sedimentation does not usually spontaneously start increasing in a system; there are reasons for increased sedimentation. On occasion there are natural system changes such as volcanic eruptions or earthquakes that cause debris flows, mud flows, and landslides, or human activities such as clear cuts that cause sudden mass movement. However, most sediment increases are gradual and are caused by changes such as land management, instream alterations, or short-term climatic events. In assessing sedimentation, evaluation of environmental change will help to identify other factors such as precipitation, discharge, shear stress, or a change in channel planform or geometry that may also accompany the sedimentation changes.

An increase in fine sediment in gravel-bed streams has been interpreted by fishery biologists as having an adverse effect on fisheries. Opinions vary as to the upper limit of the fines interpreted to have adverse effects, but particle diameters less than 6.3 mm are generally defined as fine sediment (King and Potyondy 1993). An overall decrease in fine sediment accumulation is not conclusive evidence that a system is healthy or "recovered." Fine sediment has a negative connotation because it is usually associated with the degradation of a fish population, but this sediment is a crucial part of an ecosystem. Because sediment is connected with degradation it is often assumed that "less is better," but this may not be the case. Some aquatic systems may function with high background levels of fine sediment. It is when the system is either aggrading or degrading at an accelerated rate that the sediment is usually a problem, and we should be clear whether the change is natural or human-induced.

The study of the effects of sediment is distorted when fishery habitats are managed for a single species because of its dollar value. This past orientation has caused the emphasis of the effects of fine sediment to be placed on fish and away from the effects of sediment on stream morphology and habitat structure. It may be argued that salmonids are the most sensitive fish indicators of sediment in an aquatic system, but the other organisms have not had the advantage of in-depth research and experimentation to reveal their responses. From an ecosystem perspective, we must still deal with the long-term, very real problem of excess sediment in aquatic ecosystems and the effects on aquatic habitat.

The Hillslopes

An appropriate place to begin when discussing sedimentation is at its source. Sheet & rill, gully, and ephemeral gully erosion from hillslopes are the major source of most sediment introduced into stream channels. Exceptions to this are where sediment is substantially produced by landslides, debris flows, streambanks, irrigation, and roadsides. The hillslopes are the portions of the landscape that are zones of sediment production. The movement of sediment from the hillslopes may be transport and/or supply (weathering) limited.

The most effective way to deal with the accumulation of fine sediment in aquatic habitats is to stop the excess at its source. This is feasible only for the sediment derived from accelerated erosion. If the degree of erosion has progressed too far (e.g. like gully headcuts), then accelerated erosion requires stabilization and revegetation of slopes and possibly other measures. Timing of agriculture, forestry, and construction operations with weather patterns and maintaining at least minimal levels of residual plant material on the ground are important for reducing sediment delivery to stream channels.

The Natural Resources Conservation Service, when working on sediment quantity and quality problems, should initially recognize and delineate the erosion source of sediment and establish sediment delivery rates for each type of erosion. The rate of background erosion, that which occurs in the undisturbed system, should also be determined because this will become the target goal for restoration success. If the sediment problem is severe, then instream restoration can also be addressed. If the problem is not or cannot be corrected in the water-shed, then treating the instream symptoms will be an ongoing and costly exercise.

The Streams

Once sediment has been delivered from the hillslope to the valleys and associated channels, it becomes a fluvial problem. Several issues should be addressed: (1) natural watershed sediment yield; (2) temporary versus chronic sediment problems; (3) temporary problems such as construction sites; (4) separable sediment effects (see Table 1) and quantification of these effects, which could include capitalized benefits for any proposed treatment; (5) sediment's cumulative effects and quantification of these effects; and (6) potential ways to reduce the sediment for each type of effect and comparing their effects and potential treatment cost in the action and nonaction condition. Correcting instream problems may require treating some of the other sediment problems (Table 1) as well as the stream problems. This may require spot treatment or significant channel alteration that results in short-term habitat loss. The scale of the project, both spatial and temporal, needs to be addressed.

Table 1. Types of effects from sediment delivery to soil, water, and air

I. Soil Resource (referring to consideration on land)
   A. Deposition -- Resource Consideration
      Identifiable or Predictable Problems
      1. Sediment deposition causing land damage (e.g., need to rework ground because of sediment thickness or distribution, or crop loss), on-site or off-site.
      2. Sediment deposition on roads, railroads, or bridges, causing safety problems for transportation, on-site or off-site.

II. Water Resource
   A. Water Quantity -- Resource Consideration
      Identifiable or Predictable Problems
      1. Restricted capacity from sediment deposition in small conveyances (drainage ditches, road ditches, culverts, and canals), on-site and off-site.
      2. Restricted capacity from sediment deposition in streams and lakes, on-site and off-site.
   B. Surface Water Quality -- Resource Consideration
      Identifiable or Predictable Problems
      1. Suspended sediment and turbidity.
      2. Suspended sediment or bed material having adsorbed pesticides and nutrients.
      3. Degradation of aquatic habitat for preferred species.

III. Air Resource
   A. Air Quality -- Resource Consideration
      Identifiable or Predictable Problems
      1. Airborne sediment and smoke causing safety hazards (vehicle travel on roads), on-site and off-site.
      2. Airborne sediment causing vehicle, machinery, and structure problems, on-site and off-site.
      3. Airborne sediment and smoke causing health problems, on-site and off-site.
      4. Airborne sediment causing conveyance problems in ditches, canals, and streams, on-site and off-site.

Once sediment is in the channel it is necessary to know how fast it is moving and what its effects are. It is desirable to analyze individual streams and to determine if high sediment yields are a natural phenomenon (as for example, in a decomposed granitic terrain in which the hydraulic geometry may support few pools). If this is the case, minimal action would be appropriate because instream work to create aquatic habitat would be very expensive with only limited and temporary results. If the sediment yield is higher than the natural or "background" rates, then action should be considered. Instream channel alteration to create aquatic habitat should be reserved as secondary work after the usually less expensive watershed treatment effects are analyzed. If instream action is required, a careful evaluation of treatment solutions should take place.

Other factors of importance in determining sediment impacts are the temporal variations of sediment yield. Sediment can be divided into three categories that are helpful in the evaluation of aquatic systems: framework bedload, matrix bedload, and suspended load. This categorization works well for heterogeneous sediment with a size range of several orders of magnitude. Framework bedload refers to the larger particles that are moved only during large flow events. They create the structure of the bed. The matrix bedload refers to that part of the bed material that is small enough to be frequently entrained by low to moderate flows but is large enough to settle out of the water column in lower velocities. This also includes sediment deposited by intragravel flow. This would incorporate the sand and silt size material. The matrix bedload is often referred to as "sediment" by fisheries biologists and is the size class that is of most interest and concern in fisheries studies. The suspended load is the smallest size class of the total sediment load of a fluvial system. It is held in the water column as suspended material for extended periods of time. The conditions when this material is deposited are usually slow-moving water, intrusion when a higher part of the bed is encountered, or deposition in bars and on floodplains.

As an example, assume that there has been a large storm event where all of the material on the bed of the channel has been disrupted and moved. Now the storm is over and particles begin to deposit on the bed of the channel. The largest, or framework material, will deposit first on the streambed and on bars. There is void space between these large particles. The matrix material then begins to settle out, filling in the voids with fine material. Water also moves through the permeable framework gravels below the surface. Because the movement of water through bed material is slower than in the open channel, more material is deposited in the interstices of this gravel, filling the voids even more. These are the basic dynamics of bed formation in an active creek after high flows.

Many species of fish spawn in gravel, depositing eggs in the void spaces between the framework particles. The eggs require fresh, moving water to survive and grow and then an escape route after they have hatched. If the matrix fills in these spaces, mortality rates of the fish eggs become very high. When the fish deposit their eggs they create an area free of fine matrix material by using their bodies to wash the gravel. These areas are called redds. Because of the indentation that they make in the bed, the water eddies and actually flows upstream over and through the redd, providing water and associated sediment with a lower, less damaging velocity than the main channel flow. The fish create a microenvironment within the streambed, but the degree of bed inundation varies by species. For example, Chinook salmon dig their redds to depths ranging from 8 to 14 inches (Beauchamp et al. 1983). In contrast, Cui-ui suckers lay their eggs essentially on the streambed, and some of the eggs fall down within the available pore space (Jones and Stokes 1990); other fish species, such as the slackwater darter found in Alabama and Tennessee, require shallow, marshy areas for spawning with vegetation providing the depository for eggs (Mitsch and Gosselink 1993). In this fine balance between discharge, velocity, and bed material, spawning has been very successful. Researchers have consistently found that the introduction of excess matrix bedload can have disastrous results for the spawning habitat of fish that require gravel substrate for spawning and for the habitat of gravel-dwelling benthic organisms.

Types of streams and planform characteristics

There are many ways to classify streams, based on stream geometry, flow, and planform characteristics (Leopold and Wolman, 1957; Lane, 1957; Schumm, 1963, 1977, 1981; Brice and Blodgett, 1978; Rosgen, 1994; Montgomery and Buffington, 1993; and others). Some of these systems are based on discharge, sediment transport, gradient, bed material size, stream geometry, and other physical properties of streams. Leopold and Wolman (1957) proposed a classification scheme based on flow and broad-scale geometry. Their three major categories are braided, meandering, and straight. Although this appears to relay very little information, the definition of these three channel types provides more than the planform type on a general level. Schumm (1963) proposed a scheme to divide streams into three categories: bedload channels, mixed-load channels, or suspended-load channels. This is limiting because it refers to the type of sediment transport occurring, which is difficult to determine. Inferences can be made about these channel types but will be purely supposition; however, the system did separate streams by the width-to-depth ratio and sinuosity, which is a first step to describing streams by hydraulic geometry. Probably the most comprehensive system of stream classification that uses measurable stream morphology variables and is applicable over broad hydrophysiographic provinces and various sizes of streams is the Rosgen (1994) "Classification of Natural Channels."

The Rosgen classification system (Figure 1) is useful as a mechanism to communicate information about streams that by definition fall within a range of hydraulic geometry characteristics. The system also allows for interpretation of the planform characteristics of channels (Figure 2) that have habitat value. In addition, the stream types themselves can be used to some degree (Table 2) to separate out degraded conditions resulting from channel changes or sediment load conditions. However, management interpretation based on stream types should be used with caution and with a clear understanding of field conditions and direction of change. In most situations, local streambank stabilization structures or entire streambank reconstruction should be done in the context of stream types.

A detailed evaluation of the planform characteristics of streams has been developed by Montgomery and Buffington (1993), Figure 3. Each bed form, such as the types shown in Figure 4, provides hydraulic roughness elements and the stable channel configuration for a given regime of sediment supply and shear stress. The six alluvial channel reach types (cascade, step-pool, plane bed, pool-riffle, regime, and braided channels) in large part separate different spawning and rearing habitats as well as different benthic habitats.

There are certainly variations in bed form characteristics with changes in the river regime. For example, at low-flow conditions, pools appear as flat reaches with slow flow and riffles as steeper reaches of higher velocity (Montgomery and Buffington, 1993). In contrast, studies have shown that as discharge increases, the velocity across pools increases faster than across riffles, so that at bankfull discharge the flow over pools exceeds that over riffles (Keller 1971). At these higher flows, shear stresses are greater in the pools than in the riffles; this keeps the pools scoured and maintains the channel pattern. On the receding limb of the hydrograph, the opposite process occurs and the deposition of matrix bedload in pools is reestablished. There will be associated impacts on spawning and rearing habitat with the changes in flow regime, as with benthic habitat.

The general relationship of large woody debris to planform characteristics is also shown by Figure 3. The degree to which large woody debris is transient in the channel is dominated by the degree to which the debris sticks out into the channel. A general rule is that debris that occupies less than half the width of the channel is transient (Montgomery and Buffington 1993). Where the wood is immobile, the sediment yield and associated planform characteristics are modified, as are the habitats of fish and benthic aquatic organisms.

Adjustable components of a stream system are variable with time. Relative scale determines whether a variable is dependent, independent, or interdependent (Table 3). For environmental management, a scale of 10 to 100 years is the usual period of interest or concern. An awareness of the larger time frame helps to put these variables in their proper perspective. In contrast to a time scale distribution, a hierarchical organization of stream systems on a linear spatial schedule is shown in Figure 5.

Assuming that the independent variables remain constant, emphasis should be placed on interdependent or dependent variables. These would include vegetative cover, valley slope (including channel slope and channel pattern), and channel morphology (including slope, sinuosity, shape, velocity, flooding regime, and sediment transport). Knighton (1984) uses four degrees of freedom for adjustment of channel geometry: cross-sectional form, bed configuration, planimetric geometry or channel pattern, and channel bed slope. Each of these can be addressed individually, but they are not independent of one another. A change in sediment transport can affect many of these variables or be affected by them. From this we can surmise that sediment is probably an interdependent variable.

Figure 1. Key to classification of natural rivers

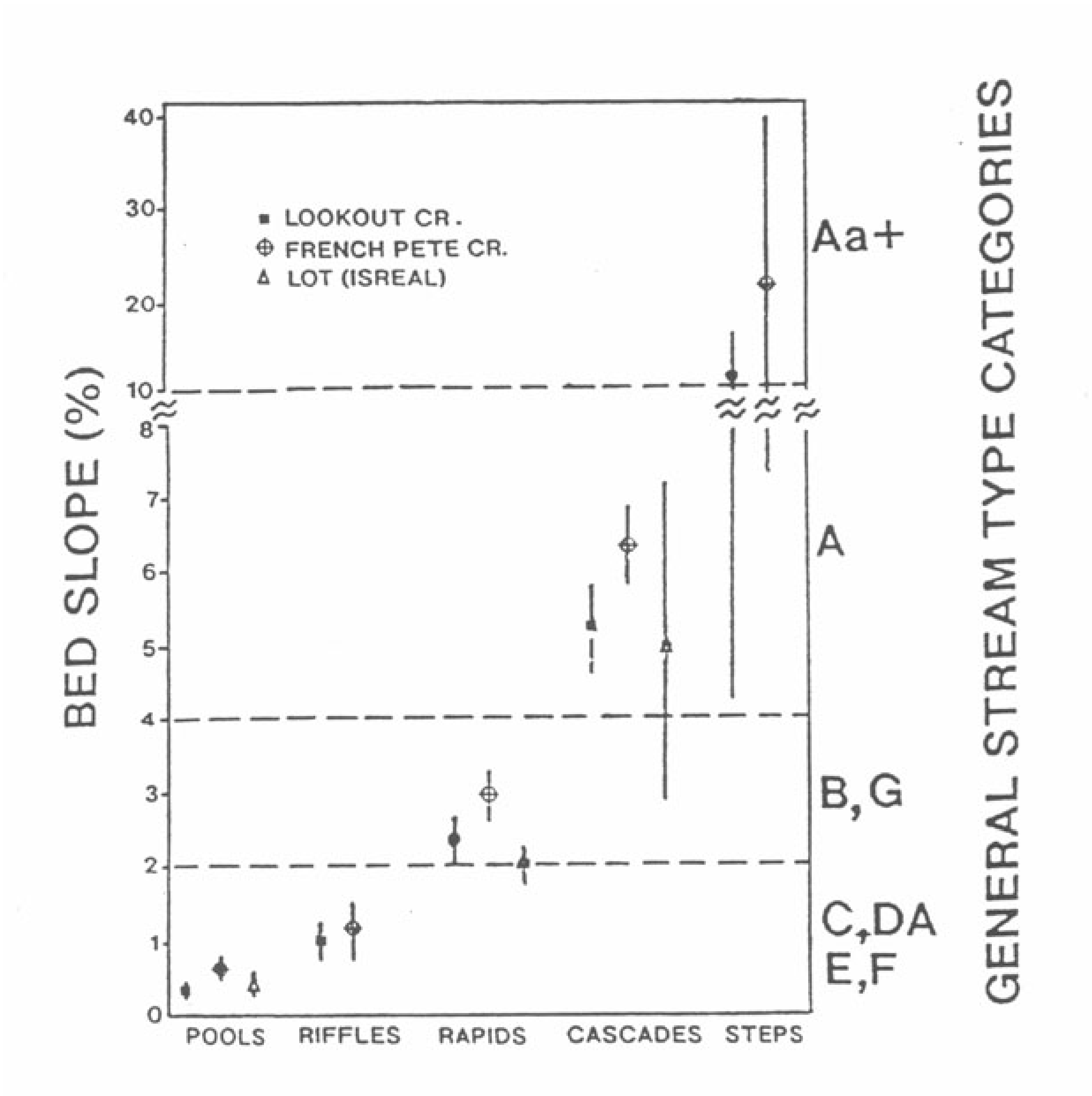


Figure 2. Relationship of bed slope to bed forms

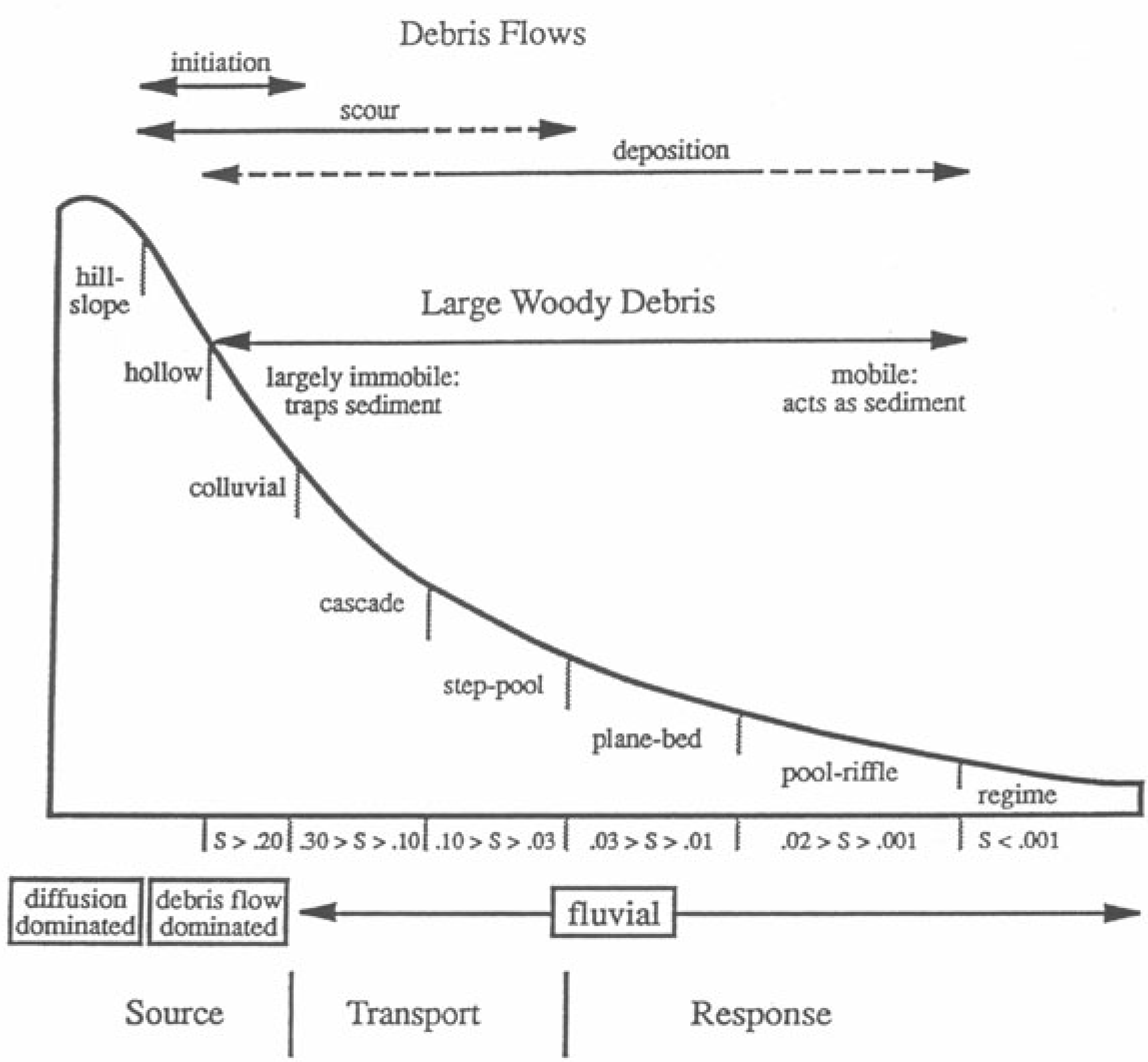


Figure 3. Idealized long profile

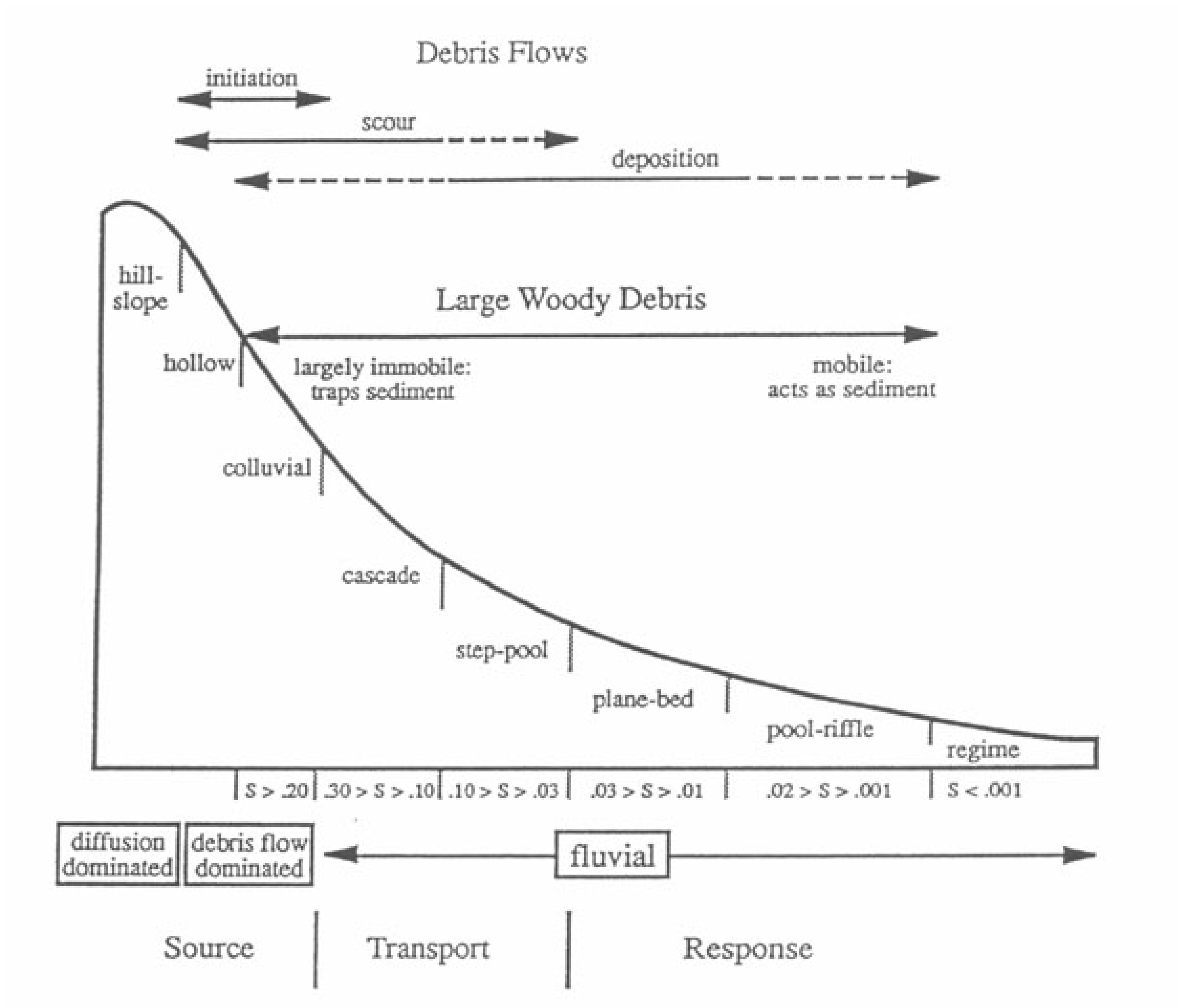


Figure 4. Channel morphologies

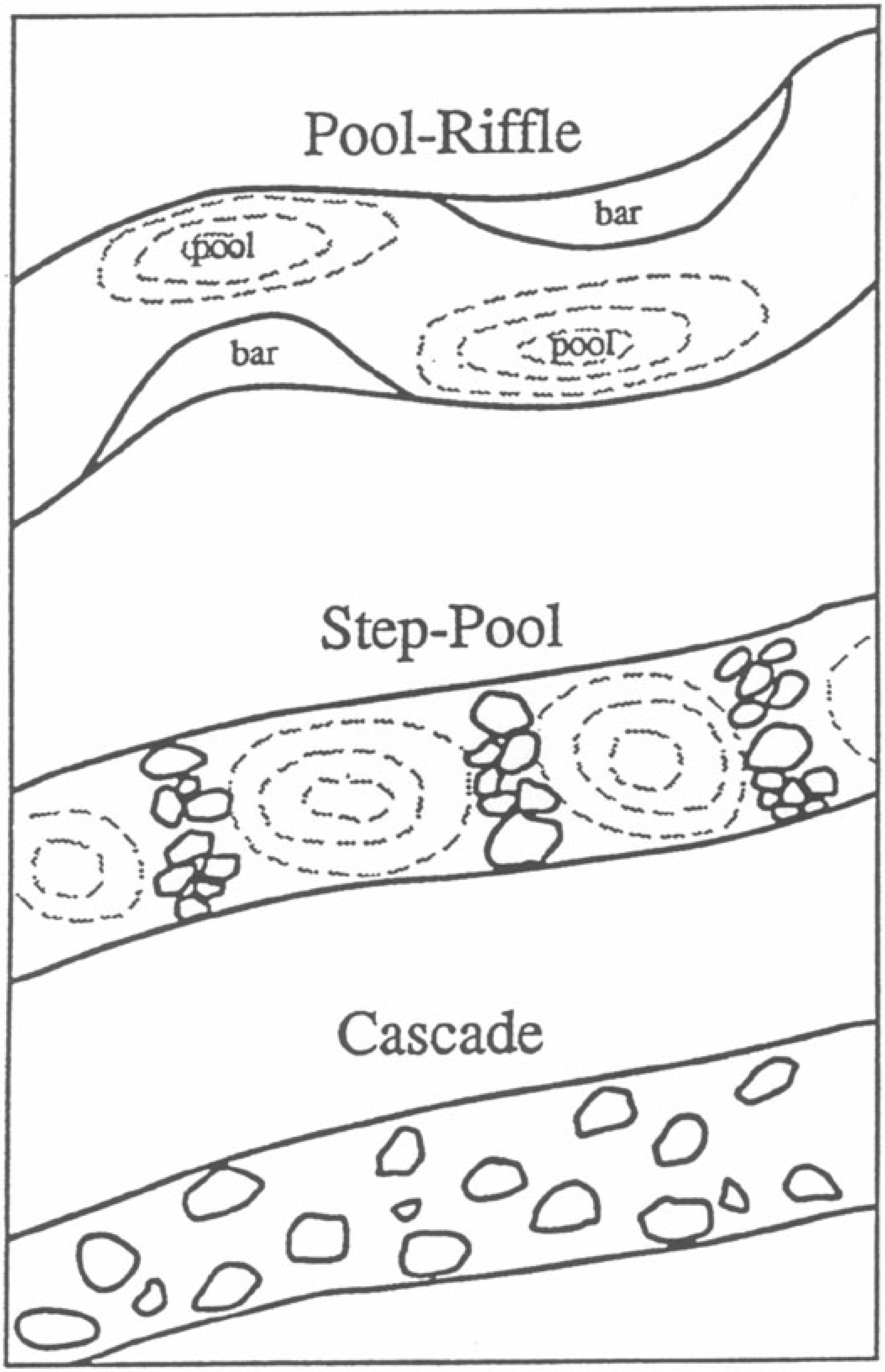
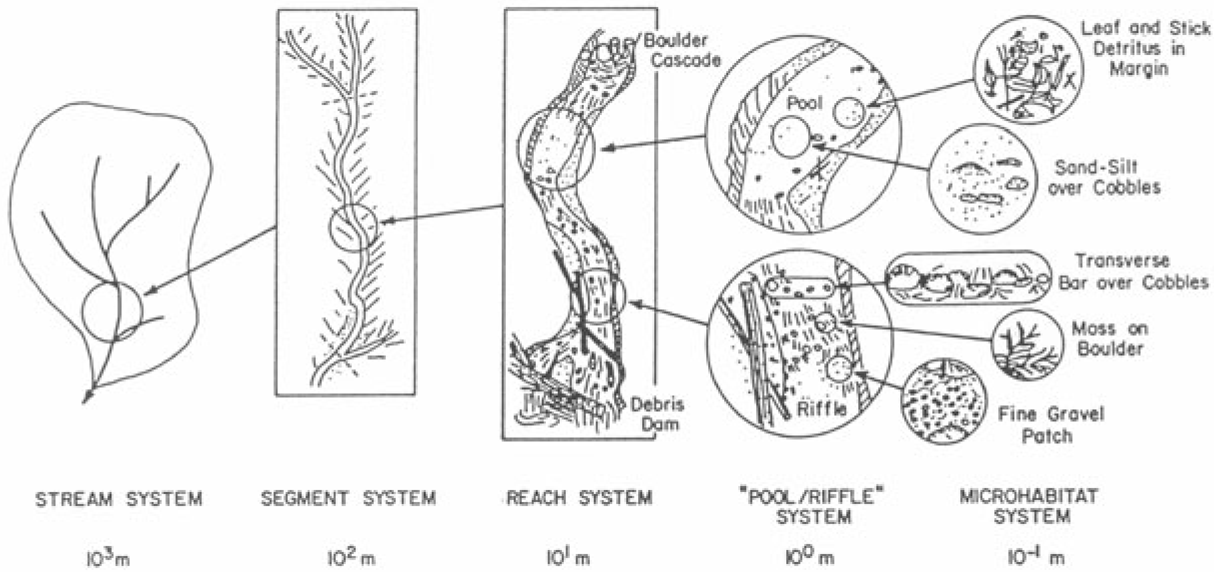

Pool-Riffle
bar
pool
bar
pool
Step-Pool
Cascade

Figure 5. Hierarchical organization of stream system and its habitat subsystems



Hydraulic and sediment characteristics of streams

The size and specific gravity of a particle dominate but do not entirely control the movement of the particle. It is necessary to understand why and how sediment moves in a fluvial system. A rough estimate can then be made of how a system will respond to a change in its sediment state.

There are two main opposing forces acting on a submerged particle. The retaining force that holds a particle in place is the weight of the particle and the vector of the drag force acting normal to the bed. The entrainment force, that force causing a particle to move, is composed of a lift force and the component of the drag force acting upwards on the particle, which is caused by eddying (Knighton 1984). Other compounding variables, such as particles surrounding the particle of interest, complicate this seemingly simple relationship between two opposing forces.

The shape of the particle is also important for transportability. If a particle is flat, it will be harder to entrain than if it were spherical. The most easily entrained particle is fine sand. Sands are very spherical while silts and clays are progressively flatter. Clays are platelike and are very difficult to entrain once they have been deposited. The shear stresses required to entrain a clay particle may be as large as the shear stress required to entrain a large cobble, but the difference in transport between these two particles is significant. Once a clay particle is entrained it will stay in the water column as suspended sediment. Deposition will occur only at very low to zero velocities. A large cobble requires high shear stresses for entrainment and relatively high shear stresses for transport. Once the velocity begins to drop, the particle will be deposited.

Table 2. Management interpretations of various stream types

Stream type	Sensitivity to disturbance1	Recovery potential2	Sediment supply3	Streambank erosion potential	Vegetational controlling influence4
A1	very low	excellent	very low	very low	negligible
A2	very low	excellent	very low	very low	negligible

A3	very high	very poor	very high	high	negligible
A4	extreme	very poor	very high	very high	negligible
A5	extreme	very poor	very high	very high	negligible
A6	high	poor	high	high	negligible
B1	very low	excellent	very low	very low	negligible
B2	very low	excellent	very low	very low	negligible
B3	low	excellent	low	low	moderate
B4	moderate	excellent	moderate	low	moderate
B5	moderate	excellent	moderate	moderate	moderate
B6	moderate	excellent	moderate	low	moderate
C1	low	very good	very low	low	moderate
C2	low	very good	low	low	moderate
C3	moderate	good	moderate	moderate	very high
C4	very high	good	high	very high	very high
C5	very high	fair	very high	very high	very high
C6	very high	good	high	high	very high
D3	very high	poor	very high	very high	moderate
D4	very high	poor	very high	very high	moderate
D5	very high	poor	very high	very high	moderate
D6	high	poor	high	high	moderate
DA4	moderate	good	very low	low	very high
DA5	moderate	good	low	low	very high
DA6	moderate	good	very low	very low	very high
E3	high	good	low	moderate	very high
E4	very high	good	moderate	high	very high
E5	very high	good	moderate	high	very high
E6	very high	good	low	moderate	very high
F1	low	fair	low	moderate	low
F2	low	fair	moderate	moderate	low
F3	moderate	poor	very high	very high	moderate
F4					

	extreme	poor	very high	very high	moderate
F5	very high	poor	very high	very high	moderate
F6	very high	fair	high	very high	moderate
G1	low	good	low	low	low
G2	moderate	fair	moderate	moderate	low
G3	very high	poor	very high	very high	high
G4	extreme	very poor	very high	very high	high
G5	extreme	very poor	very high	very high	high
G6	very high	poor	high	high	high

1. Includes increases in streamflow magnitude and timing and/or sediment increases.
2. Assumes natural recovery once the cause of instability is corrected.
3. Includes suspended load and bedload from channel-derived sources and/or from slopes adjacent to the stream.
4. Vegetation that influences stability of the width-depth ratio.
   (After Rosgen 1994)

From this simple example it becomes evident that in a system with heterogeneous bed material the small material will be moved further than the large material and the larger material will move only short distances. This causes a coarsening of the bedload because the small material is preferentially moved out of the system or winnowed. The sediment supply controls the character of the bed along with transport capacity and capability. Transport capacity refers to the amount of material that a stream can transport, and capability refers to the largest particle size class that a stream can transport.

Currently there is no precise method for measuring bedload transport. Several methods are in use but results of sampling vary widely. Measurements are commonly made with the Helley-Smith bedload sampler. This technique is limited by large flows, size of bed material, and access to appropriate sampling locations.

It is difficult to quantitatively describe the fluvial geomorphology and sediment transport of all streams because of the lack of fluvial determinate equations that fully describe stream behavior. However, there are hydraulic functional relationships between some stream variables that can be used to describe what generally happens along rivers. A primary functional relationship is that given by Lane (1955):

QwS Qsd50

Qw = Water Discharge
Qs = Sediment Discharge
S = Water Surface Slope
d50 = Median Particle Size of Streambed

This is logical since the ability of a stream to transport sediment depends on stream power, and stream power is proportional to the product of QsS. If Qw is held constant and a stream channel is straightened, or base level is lowered (i.e., slope is increased) then Qs must also be increased by erosion of the bed and banks, or d50 must be increased. What develops is a sediment transport imbalance where sediment transport capacity exceeds the sediment supply. Therefore, erosion becomes the negative feedback mechanism that works to restore stream channel stability by lowering channel gradient and increasing bed material size.

Conversely, if the sediment load is suddenly increased, as by removing the watershed cover by forest clear-cutting and new road construction, then slope tends to increase to accommodate the additional sediment load. This usually results in the stream channel more vigorously attacking the streambanks because of channel migration as the stream cannot transport all of the load provided. The additional sediment load from the streambanks worsens the transport problem and causes the stream to widen further. Obviously, changes in both discharge and sediment load may lead to conflicting responses, so it is not easy to precisely predict channel changes and the associated effects on habitat.

Table 3. Control at different time scales

Control	Effect	Status of control at time scales of (years)			
		10^7	10^5	10^3	10^1
Physiographic province:					
Megatectonic cycle	-- rifting, sea-floor spreading, subduction, continental collision, orogeny	I	I	NA	NA
Tectono-eustasy	-- base-level change	I	I	NA	NA
Neotectonic pulses	-- uplift, subsidence, faulting	X	X	I	I
Earthquakes	-- uplift, subsidence, faulting -- mass movements -- drainage changes	X	X	X	I
Climatic change	-- glaciation -- hydrologic cycle changes	X	I	I	I
Change in vegetation cover	-- changes in rates of sediment yield and/or runoff	X	I	I	I
Glacio-isostasy	-- base-level change	X	I	I	NA
Glacio-eustasy	-- base-level change	X	X	I	NA
Drainage basin:					
Geology (lithology, structure)	-- controls drainage pattern, slope morphology, sediment type	I	I	NA	NA
Climate	-- influences type and rate of weathering, hydrologic regime, vegetation cover	X	I	I	I
Relief	-- controls slope morphology, erosion potential	D	D	I	I
Vegetation cover	-- changes in erosion rates	D	D	D	I
Human impacts	-- changes in land cover, hydrologic system, erosion rates	X	D	I	I
Drainage network and morphology	-- influences delivery of water and sediment	D	D	I	I
Hillslope morphology	-- influences erosion rates, water	D	D	I	I

	delivery to channel, mass-movement rates				
River channel:					
Geology	-- influences valley slope, sediment type	I	I	NA	NA
Climate	-- influences runoff into channel, vegetation	X	I	I	I
Vegetation	-- influences bank stability, roughness	D	D	I	I
Human impacts	-- dams, channel modifications, water diversions	X	D	I	I
Valley slope	-- influences channel slope, channel pattern	D	D	D	I
Channel morphology (slope, sinuosity, shape, etc.)	-- influences velocity, flooding regime, sediment transport	X	X	D	I

Note:
I = independent; characteristic that operates independently of, and to some extent controls, geomorphic variation.

D = dependent; characteristic that is determined by geomorphic variation.

X = indeterminate; characteristic that is too variable to be reconstructed at the time scale.

NA = not applicable; characteristic that is not controlled by geomorphology, or that varies too slowly to be significant.

(After McDowell, Webb, and Bartlein 1991)<

Transport patterns of sediment and organic material

Sediment is transported through a fluvial system as bedload or suspended load. Suspended load is held in the water column and is transported at roughly the same velocity as the water. The bedload is transported by bouncing or rolling along the bottom of the streambed. Measuring the rate of sediment transport for suspended sediments is done by finding the discharge of the stream (Q) and the concentration of sediment in the water column. Measuring the rate of bedload transport is more difficult.

There is an ongoing debate about the way that bedload moves down a fluvial system. This is especially true for gravel-bed streams that form armor layers. A paper by Parker, Klingeman, and McLean (1982) proposed the idea of equal mobility. Equal mobility refers to a small range of discharge that moves a large range of bedload; in other words, when a threshold discharge is reached, the armor layer is disrupted and a large percentage of the bedload is moved. Although this was only to be used as a first approximation for transportation rates, the idea of equal mobility has been challenged, supported, and dismissed as nonsense. Komar and Shih (1992) refute the idea of equal mobility and, through calculations, show that equal mobility cannot occur. A compromise between these two views is given by Jackson and Beschta (1982). Their two-phase bedload transport includes both equal mobility and differential movement. During low flows small particles that are available on the stream bed are moved (Phase I).

Bedload movement is supply-limited. Phase II occurs at higher flows after the armor layer has been disturbed and a whole range of particle sizes is being transported. Bedload movement is transport-limited (Jackson and Beschta 1982).

The dynamics of bedload movement are not clearly understood. The total amount of bedload transport can be measured using a sediment interceptor (such as a vortex bedload sampler). However, the way that this sediment moves is not well understood. Migration of bedforms (such as gravel bars) is a common hypothesis for bedload movement but the exact dynamics are unknown.

The movement of organic matter through a fluvial system is more difficult to measure than sediment movement. This is because the size range is much greater (leaf litter to logs) and most organic matter is buoyant to a certain extent. Modeling organic matter transport is being attempted, but this will be a much more complex problem than sediment transport.

Streambank stratigraphy, characteristics, and types of failures

Streambanks can be extremely erodible to very resistant to erosion. Bedrock-controlled banks are extremely resistant and are not easily modified. Alluvial banks are erodible and can be modified by erosion and accretion. Of alluvial banks, there are two ends of a continuum. Cohesive banks are resistant to erosion and tend to be very steep. These contain a high percentage of clay or other cementing agents such as iron oxide. Noncohesive banks are more erodible, are composed of sands or gravels with very few fines, and may be a source for a large percentage of a stream's bedload. Most alluvial banks fall somewhere in between these two end members because their geomorphic history reflects a mixed stratigraphy.

When a streambank is interacting with a local or regional aquifer, water moves through the banks to recharge the aquifer during high flows and out of the aquifer into the stream during low flows; this establishes a base flow. If the movement of water is primarily out of the aquifer, the banks may be destabilized as winnowing of the fine material reduces the shear strength of the banks. If water moves primarily from the stream into the aquifer, the banks may become sealed with silt and clay. This occurs when there is a large suspended sediment load; the banks act as a filter for the fine sediment.

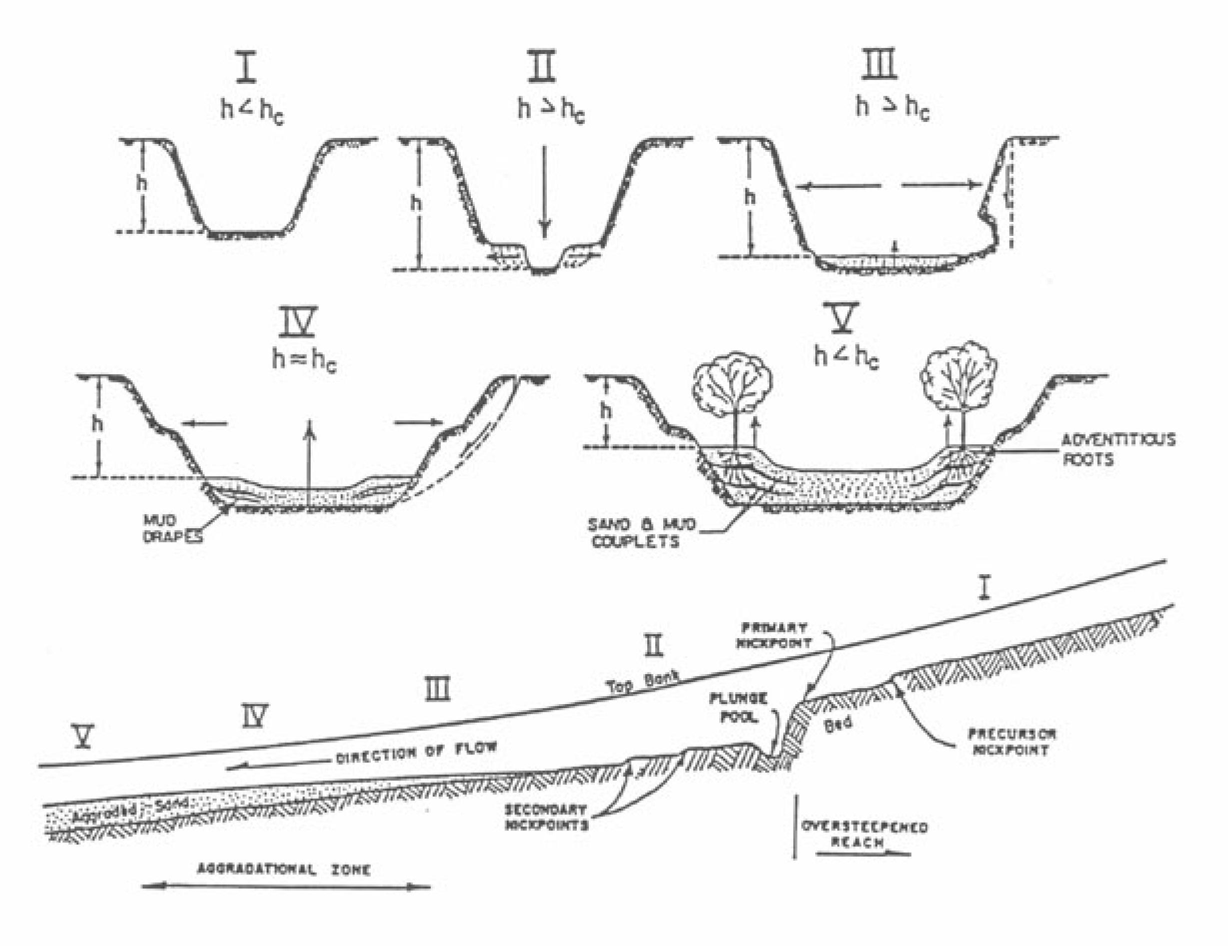
Streambanks are quite variable, and they have high sediment delivery ratios because of their proximity to the stream. Therefore, the sediment yield from streambank erosion is variable but has significant impacts on aquatic habitat. In addition, streambank stratigraphy along stream types (Figure 1) is quite variable, as are the types of failures that occur along stream channels.

Probably the most common type of streambank failures in gravel-bed streams are undercut slab failures. This occurs when the matrix material in gravel banks is removed. Once vegetative cover is removed and associated root strength is diminished, the smaller matrix material in the streambanks tends to winnow because of high flows, wave action, seepage forces coming out of the streambank, or livestock and human disturbance. Once the gravel unit is weakened and an overhang develops, the overlying units, which may be relatively stable to tractive stream forces, develop tension cracks and essentially drop vertically into the channel. This material is readily reworked by channel flows, especially those that occur at bankfull flow (1- to 2-year recurrence interval) or higher flood stages.

The streambank's erodibility is strongly influenced by the kind, amount, and character (dispersive or aggregated) of clay, the amount and size distribution of coarse particles, and the nature and amount of cementing agents (USDA, SCS, 1977). In addition, geomorphic history and climatic history since deposition of streambank deposits have a strong bearing on the streambank's stability.

For cohesive streambanks, the Channel Evolution Model (Schumm et al. 1981), shown in Figure 6, provides a good basis for evaluation of potential failure in straight stream reaches. The model shows that if the bank height (h) exceeds the critical bank height (hc), channel widening will continue.

Figure 6. Channel evolution phases.



There is no comprehensive database that reflects the degree of streambank erosion in the United States. However, there are some regional databases. For example, in the Columbia Basin in the Pacific Northwest, there are an estimated 29,800 streambank miles with at least moderate streambank erosion that needs some type of soil bioengineering treatment (USDA, SCS 1992a). The Natural Resources Conservation Service defines soil bioengineering as "the use of live, woody vegetative cuttings to repair slope failures and increase slope stability. The cuttings serve as primary structural components, drains, and barriers to earth movement" (USDA, SCS 1992b). This represents about 22 percent of the streambanks in the Columbia Basin. The National Research Council Committee on Restoration of Aquatic Ecosystems recommends a 20-year restoration target of 400,000 stream miles. This is approximately twelve percent of the 3.2 million U.S. river miles (CRAE 1992).

Aquatic habitat characteristics of streambeds

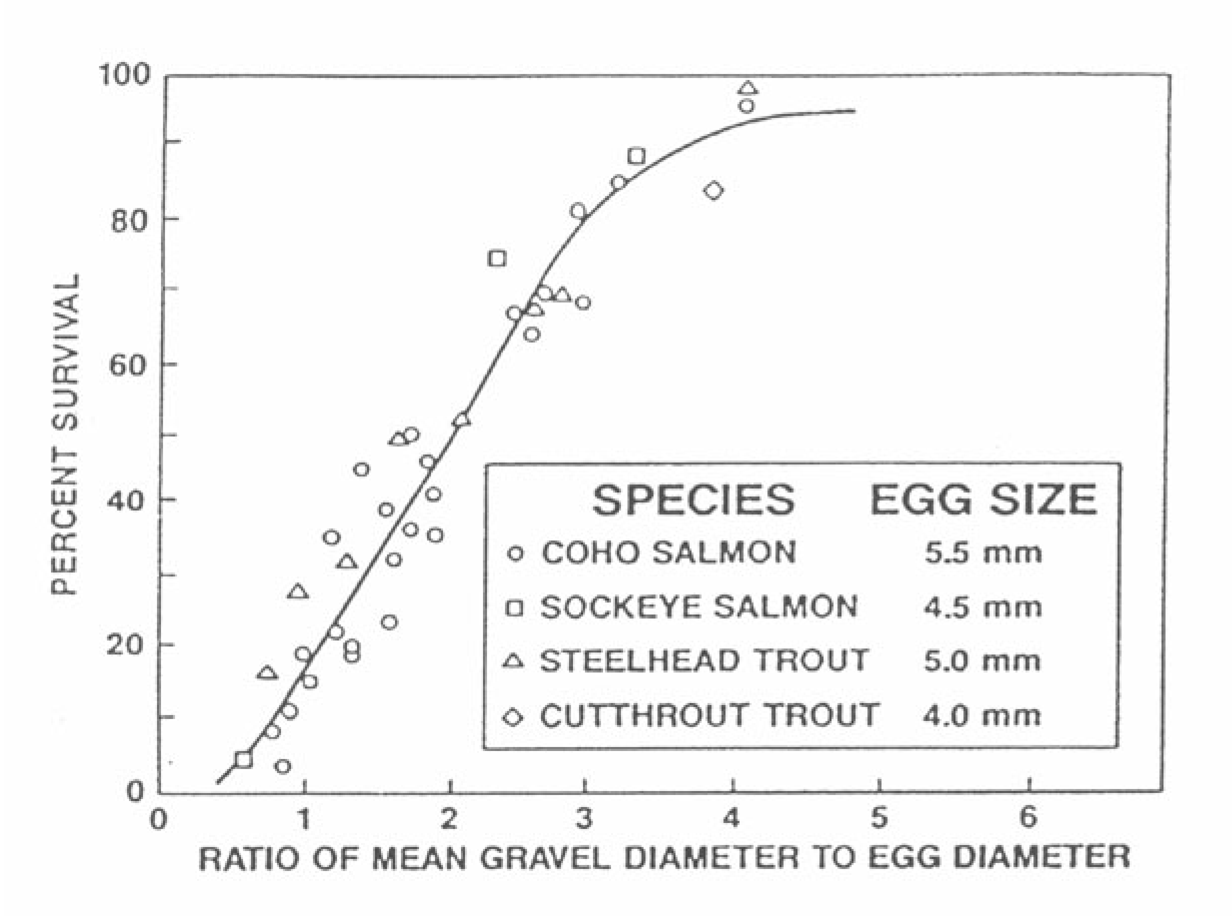
Streambed particle distributions range from boulder dominated to clay dominated. Boulder-bed streams are controlled by the watershed geology and are generally not self-formed. They are mountainous streams with high gradients and a cascade and step-pool profile. The streambed is stable during most flows and becomes mobile only at very high flows. Organic and large woody debris is important in boulder-bed streams; it creates part of the stream geomorphology and has a stabilizing effect.

Gravel-bed streams generally have a lower gradient than boulder-bed streams and are characterized by bimodal particle size distributions and armoring of the bed. There is usually constant flow through the hyporheic zone (intragravel flow). The bed is mobile up to several times a year. Winnowing of fines from the surface of the bed material forms the armor layer. This layer is more difficult to entrain because the particles are larger and are interlocked with other particles. Gravel-bed streams have large, diverse macroinvertebrate populations (ASCE 1986) and are extremely important spawning areas for anadromous fish, as indicated in Table 4 and Figure 7. The level of the macroinvertebrate population controls the fish population because it is the primary food source. An average of 70 percent of freshwater fish species depend on insects as a food source (Healey 1984). Table 5 presents a classification of aquatic trophic invertebrates (Cummins 1973). The composition of the communities of these invertebrates varies throughout the watershed, as shown in Figure 8.

Table 4. Stream reach classification based on bed material

Bed type	Partical size(mm)	Relative frequency of bed movement	Typical benthic macroinvertebrates		Fish use of bed sediments
			Density	Diversity	
Boulder--Cobble	>=64	Rare	High	High	Cover, spawning, feeding
Cobble--Gravel	2-256	Rare to periodic	Moderate	Moderate	Spawning, feeding
Sand	0.062-2	Continual	High	Low	Off-channel fine deposits used for feeding
Sand	0.062-2	Continual	High	Low	Off-channel fine deposits used for feeding
Fine material	<0.062	Continual or rare	High	Low	Feeding
(After ASCE Task Committee 1992)					

Figure 7. Salmonid embryo survival



Sand-bed streams are characteristic of larger rivers such as the Mississippi and of low-gradient, smaller rivers. There is constant movement of the bedload, which eliminates the larger macroinvertebrates. There are, however, other invertebrates that live successfully in sand-bed streams. Organic matter and snags in the stream are important breeding grounds for many of these invertebrates, which in turn provide food for fish (Minshall 1984).

Fine-bed streams have silt or clay bottoms. These types of streams are unusual in western mountainous watersheds except in the estuaries. However, in the lower topography of the Midwest they are common. Once these fine sediments have been entrained, they are generally not redeposited in the stream. This is why sand beds dominate in low-gradient streams even when the sediment load is primarily silt or clay-sized particles.

A study by Gore (1978) indicates that the highest faunal diversity of benthic macroinver-tebrates occurs in gravel-bed streams. Within the gravel-bed streams there are optimal conditions for faunal diversity. Gore (1978) found that depths ranging from 20 to 40 cm with flows ranging from 75 to 125 cm/s produced the greatest diversity (Table 6). He also assessed faunal diversity by using the Froude number and the Microprofile Index (Table 7). The Froude number is a relative index of turbulent flow. At numbers less than unity, the flow is considered tranquil; at numbers greater than unity the flow is considered shooting or rapid. Froude numbers in the range of 0.4 to 0.5 were found in conjunction with high faunal diversity (Table 8, Gore 1978).

The Microprofile Index (Table 6, Gore 1978) is a technique for measuring the relative roughness of the stream bottom for a small area (0.1 m2). This is useful for estimating the thickness of the laminar layer and the availability of protection for macroinvertebrates. High faunal diversity is found in areas with relatively high Microprofile values (Table 6, Gore 1978).

Using these four measurements (velocity, depth, Froude number, and Microprofile Index), appropriate indicator species, those with the same requirements as the conditions for highest faunal diversity for a particular area, can be identified. If the environmental tolerance limits for a specific species have a range similar to the environmental conditions necessary for high faunal diversity, that species is considered a good indicator (Gore 1978).

Using benthic macroinvertebrates as indicators for appropriate velocity ranges as shown by Gore (1978) is a concept that can easily be applied to sediment yield. Using the same techniques, proper indicator species to determine appropriate sediment levels can be identified. For example, this method would be more useful than relying on survival and emergence of salmonid embryos. The migration of salmonids from the spawning grounds introduces many confounding variables, including the effects of dams, downstream pollution problems, and commercial fisheries. Benthic macroinvertebrates would be more useful in determining the effects of sediment in an area because they are less affected by many off-site environmental conditions and human influences but are very sensitive to localized pollution loadings. Benthic macroinvertebrate populations will also reflect differences in gradient, stream geometry, and bed particle size as shown in Figure 9.

In another study, Newlon and Rabe (1977) stated that the two most important factors affecting macroinvertebrates are substrate and suspended sediment. They found that there are four to five physical and chemical factors that have significant influence over biomass and diversity of macroinvertebrates. These factors include substrate, suspended sediment, gradient, water temperature, and stream order and width. Minshall (1984) supports these findings and provides a literature review of insect-substratum relationships.

Aquatic plants are affected by both increased bedload and suspended load. An increase in bedload may bury an area in which a plant species is growing. Subaqueous plants will be significantly affected by increased suspended sediment loads because primary plant production is reduced with increases in turbidity. This results in a decrease in benthic organism diversity and density because of a limited food supply. The reduction in the benthic organism popula-tion finally results in a reduced food supply for fish and if the food (benthic organisms) is limited, the fish will migrate to other reaches of the stream. It would be possible to take data (developed on the relationship of sediment to planform characteristics and flow) to develop a habitat suitability index for various species. Data such as water temperature, dissolved oxygen, and percentage of cover would be necessary.

Sediment quality of streams

Sediment quality is another widespread problem in freshwater and marine systems (EPA 1992). Sediment quality problems can occur throughout stream types, but tend to occur where there are fine textural stream bottoms and at the lower end of the stream system (i.e. estuaries and deltas). The contaminated sediments can have both direct adverse impacts on bottom fauna, and indirect effects as the toxic substances move up the food chain.

Because of the variability of conditions encountered in stream systems, lake systems, estuaries, and oceans, a variety of tests may be needed to characterize the physical, chemical, and biological systems that may be affected. In addition, microbial and benthic species will likely reflect sediment contamination that is not revealed by sampling only fish (Burton 1988). In other words, toxic impacts may be occurring in a river, lake, estuary, or ocean, even though sampling in the water column over the sediments may show water that meets water quality standards. Because there is no single method that captures all the spatial and temporal impacts of contaminated sediment upon all organisms, a compendium has been developed to present several complementary methods to assess sediment contamination (EPA 1992).

Table 5. A general classification system for aquatic invertebrate trophic categories

General category based on feeding mechanism	General particle size range of food (microns)	Subdivision based on feeding mechanisms	Subdivision based on dominant food	North American aquatic invertibrate taxa containing predominant examples
Shredders	$>10^3$	Chewers and miners	Herbivores: living vascular	Trichoptera (phyganeidae, Leptoceridae)

			plant tissue	Lepidoptera Coleoptera (Chrysomelidae) Diptera (Chironomidae, Ephydridae)
		Chewers, miners, and gougers	Detritivores (large particle): decomposing vascular plant tissue; wood	Plecoptera (Filipalpia) Trichoptera (Limnephilidae, Lepidostomatidae) Diptera (Tipulidae, Chironomidae)
Collectors	<10^3	Filter or suspension feeders	Herbivore - detritivores: living algal cells, decomposing organic matter	Ephemeroptera (Siphlonuridae) Trichoptera (Philopotamidae, Psychomyiidae, Hydropsychidae, Brachycentridae) Lepidoptera Diptera (Simulidae, Chironomidae, Culicidae)
		Sediment or deposit (surface) feeders	Detritivores (fine particle): decomposing organic matter	Ephemeroptera (Caenidae, Ephemeridae, Leptophlebiidae, Baetidae, Ephemerellidae, Heptageniidae) Hemiptera (Gerridae) Coleoptera (Hydrophilidae) Diptera (Chironomidae, Tabanidae)
Scrapers	<10^3	Mineral scrapers	Herbivores: algae and associated material (periphyton)	Ephemeroptera (Heptageniidae, Baetidae, Ephemerellidae) Trichoptera (Glossosomatidae, Helicopsychidae, Molannidae, Odontoceridae, Goeridae) Lepidoptera Coleoptera (Elmidae, Psephenidae) Diptera (Chironomidae, Tabanidae)
		Organic scrapers	Herbivores: algae and associated material (periphyton)	Ephemeroptera (Canidae, Leptophlebiidae, Baetidae, Heptageniidae) Hemiptera (Corixidae) Trichoptera (Leptoceridae) Diptera (Chironomidae)
Predators	>10^3	Engulfers	Carnivores: whole animals (or parts)	Odonata Plecoptera (Setipalpia) Megaloptera Trichoptera (Rhyacophilidae, Polycentropodidae, Hydropsychidae) Lepidoptera Coleoptera (Dytiscidae, Gyrinidae) Diptera (Chironomidae)

		Piercers	Carnivores: cell and tissue fluids	Hemiptera (Belostomatidae, Nepidae, Notonectidae, Naucoridae) Diptera (Rhagionidae)

Figure 8. Composition of aquatic organism communities by stream order

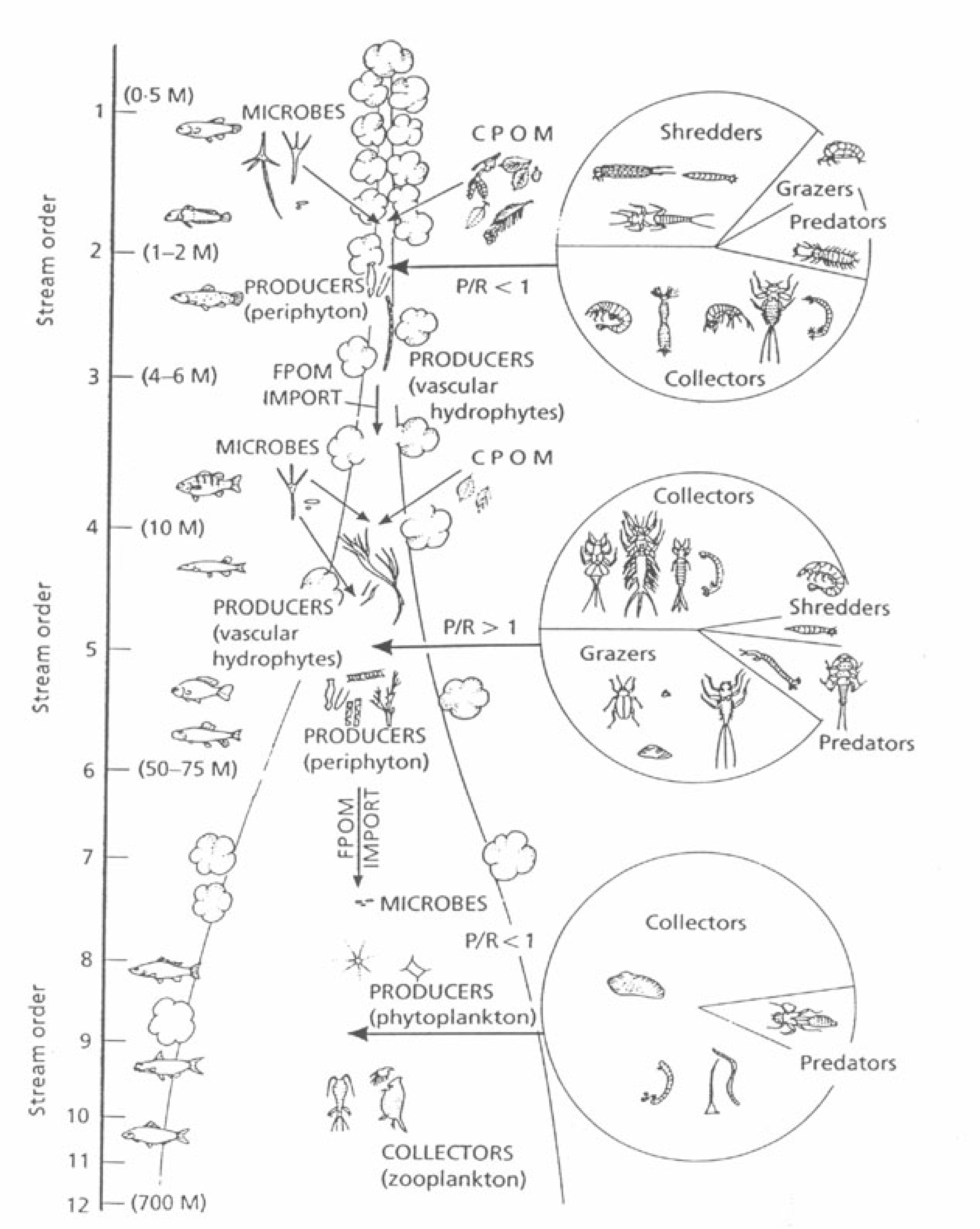


Table 6. Average faunal diversities for increments of depth and current velocity

Velocity	Depth (cm)				

(cm/s)	0-10	10-20	20-30	30-40	40-50
>120	0.541	1.802	2.131	2.301	1.817
105-120	1.386	1.661	2.612	2.027	1.724
91-104	1.203	1.983	2.211	1.844	2.072
76-90	1.652	1.809	2.319	2.190	2.156
61-75	1.523	1.703	1.728	2.034	1.612
46-60	1.440	1.721	1.605	1.958	1.812
31-45	1.628	1.893	1.977	1.933	1.845
16-30	1.348	1.218	1.957	1.054	1.505
0-15	0.667	1.112	1.405	1.530	1.371
(After Gore 1978)					

Table 7. Characteristics of the Microprofile Index (MI)

MI	Profile Type
0-0.5	Smooth
0.5-1.0	Moderately smooth (gravel)
1.0-1.5	Small cobbled
1.5-2.0	Smooth, medium cobbled
2.0-2.5	Rough, medium cobbled
2.5-3.0	Large cobbled
3.0-4.0	Bouldered
4.0+	Critical (angular boulders)
(After Gore 1978)	

Table 8. Average faunal diversities for microprofile and turbulence

	Microprofile Index					
Turbulence	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-4.0
>0.7	1.476			2.025	1.750	
0.6-0.7			2.111	1.875		2.600
0.5-0.6		2.763	2.040	1.560	1.072	

0.4-0.5	1.946	2.080	1.745	2.017	1.959	3.366
0.3-0.4	1.310	1.871	1.689	1.978	2.064	
0.2-0.3		2.119	2.099	2.000	1.657	
0.1-0.2	1.609		1.356	1.400	1.995	
0.0-0.1		1.399	1.327	1.744		
(After Gore 1978)						

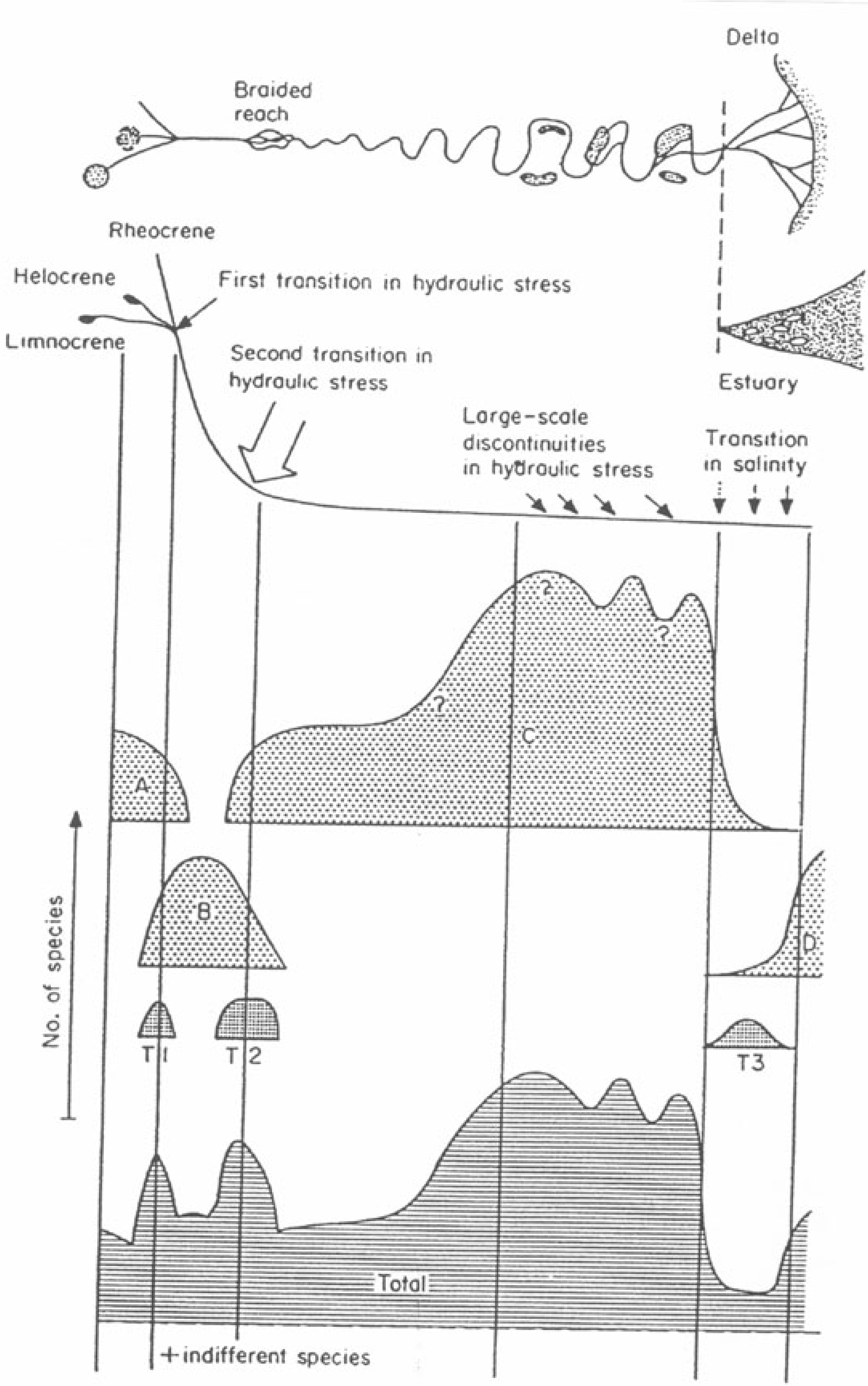
Some states (Oregon, DEQ, 1992) have proposed a tiered evaluation to determine potential sediment contamination. Their approach starts with an analysis of the physical properties to determine where the fines (i.e. silts and clays) and organics are located in the depositional areas.This is Tier I testing. Once the fines are located, a chemical analysis can be conducted based on potential categories of problems (metals, pesticides, coliforms, PCB's, and hydrocarbon derivatives), which is Tier II testing. If the chemical level exceeds established standards or toxic thresholds established by the scientific community, then a third level of testing is indicated. This Tier III level is bioassays. Obviously, if there are already known contaminant areas, Tier I or even Tier II could be bypassed and testing would start at Tier III.

Determination of trends in sediment quality depends on sampling over long periods of time. If long-term sample results are available, trends can be established, but this may be complicated by changes in analytical methods over the time frame. This has been a particular problem with some metals such as cadmium.

Current status of research

During the past decade, research in the area of stream sediments has focused almost entirely on the effects of fine sediment on salmonid spawning. The trend seems to be to greater quantification and greater accuracy in testing and monitoring. There have been recent studies of macroinvertebrates, which are becoming an important factor in aquatic habitat evaluation as it relates to fish.

Figure 9. General faunistic zonation patterns of the benthos in pristine streams



Delta
Braided reach
Rheocrene
Helocrene
First transition in hydraulic stress
Limnocrene
Second transition in hydraulic stress
Estuary
Large-scale discontinuities in hydraulic stress
Transition in salinity
?
?
?
C
A
B
D
No. of species
T1
T2
T3
Total
+indifferent species

A comprehensive paper on the effects of sediment on aquatic habitat was written by Alexander and Hansen (1986). The focus of the paper is on brook trout but the methodology provides a complete and comprehensive review of their particular study area. This study encompassed 15 years' worth of work with daily monitoring and measurements. Instead of moving fish embryos to a lab setting, Alexander and Hansen introduced sand into a stream system for a total of 5 years and monitored the response of the aquatic habitat. They collected aquatic data for 5 years prior to the experiment and continued the monitoring after the introduction of sand was halted. This provided data before, during, and after the excess fines were introduced into the low-gradient stream. Besides measuring the effects on brook trout, Alexander and Hansen (1986) also studied the effects on the macroinvertebrate population. While not being overly quantitative, the data are complete enough to draw strong conclusions with statistical significance.

A review paper written by Kondolf and Wolman (1993) provides an excellent overview of salmonid spawning-gravel sizes. This is a literature review of 22 sources that reported particle-size distributions for many fish species. Kondolf and Wolman (1993) analyzed the data and plotted cumulative size distributions to calculate particle size mean, geometric mean, sorting index, skewness, and graphic mean. The limitations of their study and studies that they analyzed were adequately discussed. The paper is mostly a discussion of the statistical tests that were performed, but it is an excellent source of data because only 4 of the 22 sources are in open literature (Kondolf and Wolman 1993).

Recommendations for future research in streams

Evaluating the health of a stream system is difficult, and it is not possible to do an in-depth and thorough investigation each time an evaluation is necessary. This requires other, less intensive techniques for monitoring. Fish have been used as indicator species. As the number of fish declines, a system is thought to be degrading. It takes at least a season to monitor and compare differences in populations of fish. Because of the number of factors that influence fish (dams, fishing, and pollution for example) it is difficult to evaluate the effects of a single component in the system.

Fish are not great indicators of excess sedimentation. Separating the effects of sediment from other environmental factors can be impossible in a natural system. Sometimes the effects are obvious when there are excessive amounts of fine sediment, but often they are not apparent. A slight decline in the fish population may be attributed to sediment but may actually be the result of dams in the stream system. To eliminate this problem, other indicator species should be found. Those species are preferable that are more sensitive to very small changes in sediment quality and quantity, less mobile, and have shorter life cycles. This would allow more frequent monitoring which would produce information about sediment in a limited geographic area.

Gore (1978) presents a technique that determines tolerances of benthic macroinvertebrates to water depth and current velocity. This same technique could be employed to determine the tolerance of specific macroinvertebrates to fine sediment. Gore (1978) was able to find an indicator species (Rhithrogena hageni) that had tolerances closely matching the depth and current conditions for optimum community diversity. Finding sediment-sensitive macroinvertebrates seems to be the next logical step for monitoring of fine sediment in stream systems.

There seems to be a lack of negative data in the literature. Studies that have been completed and have failed to produce positive results generally are not published. This is a tremendous source of data that are being lost. If these data were available, many researchers could save time and energy by learning from previous mistakes. Negative results should not be viewed as failure, but as a valuable learning experience which furthers the goals of research. In addition, there is also a significant lack of long-term data, and there are few studies that are ongoing. Short studies provide a great deal of information but they need to be monitored to determine their relative effectiveness or value. This can be accomplished by an ongoing study that is maintained for many years, or it can be accomplished by later studies in the same area.

The Lakes and Reservoirs

Research focusing on aquatic effects of sediment in lakes and reservoirs is limited. This is especially true for research in the Western United States. Lakes in the Northeastern United States have been more thoroughly studied because of the influence of the Great Lakes region. The emphasis in lake studies is different from studies of the stream environment. Because lakes are sediment sinks and essentially closed systems (for sediment), toxins are of great concern. Once a lake has been polluted, it is difficult to clean. Sediment is important in these environments because many inorganic toxins bind to fine sediments. A large percentage of lake sediment literature is aimed towards sediment toxicity.

Lake pollution generally gains local but not regional or national interest. This is a result of ecologic isolation; if one lake is polluted or destroyed, it usually does not have an impact on other systems unless there is a stream emanating from the lake. Concern does arise on a regional or national level when megafauna, such as birds or deer, are affected. This is very different from streams which express environmental changes throughout their systems.

Types of lakes and reservoirs

Lake and reservoir classification systems can be described using five broad categories. These include but are not limited to (1) origin, shape, and location, (2) physical properties, (3) chemical properties, (4) assemblage of fish species and fish habitat, and (5) trophic status (Leach and Herron 1992).

The origin, shape, and location of natural lakes can be the result of geomorphology, climate, or local/regional geology. Classification by origin (usually the geologic history) was popular during the nineteenth and early twentieth centuries (Leach and Herron 1992). Although lake origin may be interesting to the physical scientist, it does not convey information about the habitat type of the lake. Lake morphometry and morphology (shape) is a classification type similar to lake origin; however, morphology and morphometry can be quantified. The size and shape of a lake do reflect, in part, the aquatic habitat available in the lake, but it is primarily a physical description. The location of a lake may be important on a global scale (tropical versus arctic) but is less important on a regional scale. Early limnologists had two main categories for lake location: caledonian-subalpine and baltic. This was soon proved to be useless because two lakes, one from each category, were found closely situated in Germany (Leach and Herron 1992).

The physical properties of lakes include thermal mixing and optical characteristics. One of the first thermal classifications was by Forel (1892) and was limited to temperate, tropical, and polar. This system was later expanded to differentiate between ice-covered lakes, stratification, and frequency of mixing (Leach and Herron 1992). Optical characteristics refer to the depth of light penetration. The more organic material or inorganic sediment in the water, the less light will penetrate. This observation has been incorporated into trophic classification because low light penetration generally correlates with high trophic levels (biologic productivity). This can be misleading because high levels of suspended inorganic sediment may be found in a lake with very low trophic levels. This is also true for very deep lakes which have low light penetration and low trophic levels. Wiederholm (1984) found that high inputs of mineral sediments can actually cause oligotrophication of lakes (a net reduction in biologic productivity).

Chemical properties include edaphic inputs and water quality. Classification by edaphic inputs is useful in areas where there has been significant human disturbance. Urban lakes, forest harvesting, and agricultural practices are the types of uses that would favor lake classification by edaphic inputs. The amount and distribution of total dissolved solids are the decisive criteria in an edaphic classification system. Water quality has also been important for heavily utilized lakes. Typical classifications include relative pollution categories for bathing, consumption, fishing, irrigation, and aquatic habitat (Leach and Herron 1992). The water quality classification is used primarily for human protection.

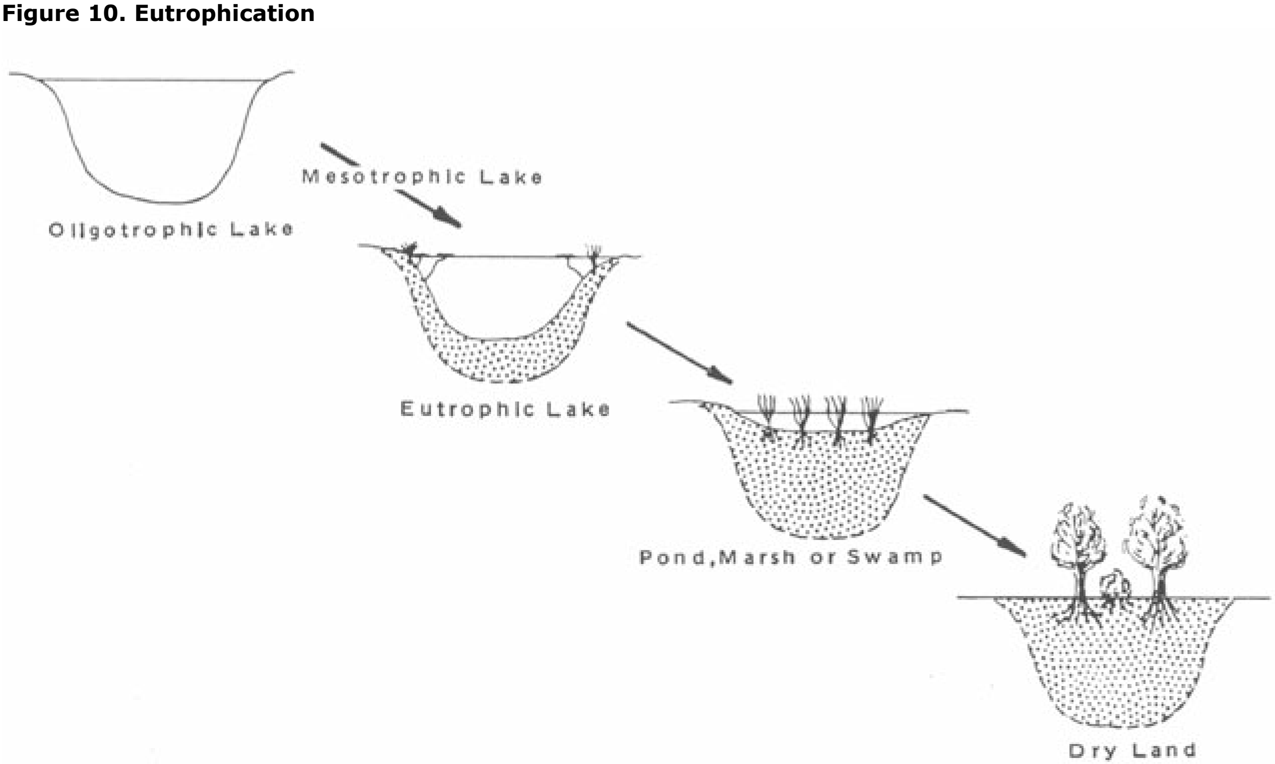
Classification by assemblage of fish species and fish habitat is specialized for fishery managers and can be modified for local conditions or management needs (Leach and Herron 1992). The type of fish present in a lake is somewhat informative of the type or quality of habitat available but it is relatively subjective. This is especially true for lakes which are stocked with hatchery fish. This classification system may be very useful for fishery managers but has limited application for land-use managers and other non-fishery people.

Trophic status is one of the most widely used and accepted systems for lake classification. There are three fundamental trophic levels: oligotrophic, mesotrophic, and eutrophic. Trophic status can be determined by (1) a single parameter such as phosphorus levels, (2) composite indices such as the Quality Index, which includes many single parameters, (3) biologic indicators such as benthos, or (4) regional typologies which include local inputs and perturbations (Leach and Herron 1992).

Oligotrophic lakes are low in biological productivity and total nutrient availability. These are typically deep, cold lakes with limited phytoplankton. Salmonids and whitefish are native to oligotrophic lakes. Eutrophic lakes are the opposite extreme. Biologic productivity is high and the nutrient load is also high. Lack of dissolved oxygen may occur in the deeper parts of a eutrophic lake because of thermal stratification. When lake temperatures are homogenous or the surface water is colder than the deep water, mixing occurs. If the deep water is colder than the surface water, no mixing will occur and the deeper water is essentially isolated from the oxygen and nutrients of the surface. This stratification is normally seasonal and occurs during the summer months. Warm-water fish, such as perch, pike, and bass, are native to eutrophic lakes (EPA 1973).

The evolution of natural lakes is normally from oligotrophic to eutrophic (Figure 10). This results from the delivery of sediment and nutrients to the lake, which slowly causes the lake to fill in and become shallower. This generally causes an increase in temperature and biologic productivity. Lakes in transition between oligotrophic and eutrophic states are mesotrophic. Some lakes, such as glacial lakes or very large, deep lakes, remain oligotrophic; however, human activity has caused an acceleration of eutrophication even for lakes that would normally remain oligotrophic (EPA 1973). An increase in sediment delivery to lakes can accelerate the eutrophication process because of nutrients that bind to fine sediments. Continued filling with sediments leads to advanced eutrophication, swampy or marshy conditions, and finally total infilling of the prior lake environment.

Figure 10. Eutrophication



Hydraulic and sediment characteristics of lakes

Particle-size trends in lakes are more predictable and stable than sediment in streams. In a perfectly round lake, sediment would be segregated into concentric circles with the coarsest material near the edge and gradual fining towards the center; this is called sediment focusing. Particle-size trends in lakes do not usually represent short-term variations in sedimentation but are integrations of longer periods of time (weeks to months) (Herdendorf 1992).

Particle-size distributions in lakes can be a useful tool for interpreting the aquatic environment. Generally, particle size decreases with decreasing hydraulic energy. However, relict sediment may imply a high-energy environment when a low-energy environment actually exists or vice versa. An example is lag gravel from an old stream deposit. If there is sufficient pore space for fines to deposit in, the gravel may remain exposed, suggesting a high-energy environment. Coarse sands and sandy gravels are good indicators of high-energy environments if they are modern deposits. They are also good indicators of active sediment transport (Herdendorf 1992).

The direction of sediment transport can be determined from the direction trend of the deposited sediments. A well-established particle-size trend or a relict sediment deposit is a good indication of a stable environment. The characteristics of sediment deposits are dependent on sediment supply, so if a particle size class is missing, it may not be the result of hydraulic energy patterns but rather the result of sediment availability (Herdendorf 1992).

Particle-size trends are very useful as sediment transport indicators but they are poor evidence for erosion and deposition. To evaluate erosion and deposition trends, profile changes or bed-elevation changes should be monitored (Herdendorf 1992). Other factors affecting erosion, deposition, and particle-size trends are boat wakes, recreational use, industrial use, dredging, and other human influences. All factors affecting hydraulic and sediment characteristics, usually including the human factor, should be addressed when a lake sediment evaluation is necessary.

Aquatic habitat characteristics

Regional classification of lakes is probably the best first-order approach to describe lakes according to their aquatic habitat characteristics (Leach and Herron 1992). This allows certain variables (climate and geology for example) to be held constant within a geographic area. However, aquatic habitats within lakes can be very diverse and complex and may require detailed field analysis to describe the lake characteristics accurately.

The history of the lake formation, combined with its current hydraulic condition, to a large extent controls biologic suitability. An example is an exposed clay surface which has hardened and cracked and then been resubmerged. This provides a "bedrock" environment rather than a fine-sediment environment. The benthic invertebrates living in such an environment may be different from the expected species based on preliminary examination of the lake substrate.

Under normal environmental conditions, benthic invertebrates can move quickly enough to keep ahead of fluctuations in natural sedimentation. Artificial dumping and/or accelerated sedimentation introduces too much sediment too quickly for benthic invertebrate organisms to avoid it (Herdendorf 1992). Case-dwelling mobile macroinvertebrate species can do very well in areas of rapid sedimentation because of the decrease in competition and their ability to escape the sediment (Wiederholm 1984). Loss of benthic communities may also occur if an increase in wave action erodes the substrate (Herdendorf 1992).

Preferred spawning habitat in lakes can be similar to that in streams, but because of the diverse and relatively more stable environment, spawning occurs in a large variety of substrates. Lake trout in Lake Huron prefer cobble and rubble and do not generally use coarse sands or gravels to spawn. Lake trout, like stream trout, cannot successfully spawn in areas that are blanketed with fine sediments (Nester and Poe 1987). Other lake species prefer sand, rocks, inshore environments, logs, sticks, plants, or vegetative nests (Herdendorf 1992).

Lag cobbles or gravels are often used for spawning while modern deposits may be avoided. Lag deposits are usually stable, while modern deposits may still be actively transported (Herdendorf 1992). Areas that meet the size criteria for spawning grounds may not have the appropriate stability. The relative location of spawning grounds is important in large lakes. Large substrate material combined with strong wave action is preferable. Spawning grounds are generally located near deeper water (>15 meters) (Nester and Poe 1987) where wave action is the strongest. This provides an environment where the spawning grounds are flushed with water and are supplied with oxygen and nutrients.

Determination of important feeding and spawning grounds in lakes should be made by consistent and sound sampling and monitoring methods. Identification of suitable habitat for feeding and/or spawning based on substrate characteristics is probably insufficient because of seasonal variability and the complex interactions between the physical and biologic environments.

Sediment quality of lakes

Sediment quality in lakes is extremely variable geographically. The introduction of excess fine sediment can be addressed in lake tributaries or in the watershed, but the actual sediment quality is difficult to alter because once it is in the lake, it is hard to remove. Sediment traps such as filter dams and desilting basins can be used in the tributaries above a lake to reduce the amount of fine sediment that is delivered to the lake (EPA 1973).

Dredging of lake bottoms is often considered as a remedial technique to remove excess sediment, increase lake depth, or remove toxic or nutrient-rich sediment from the lake environment. There are many problems associated with dredging lake bottoms. Dredging temporarily increases turbidity in the lake and can cause environmental degradation because of the decrease in primary productivity. The sediment may be a nutrient sink and dredging may reintroduce the nutrients back into the lake. The interstitial water may also be high in nutrients or toxins, and removing this interstitial water is very difficult and expensive. The loss of shallow zones may result in the loss of large macrophyte beds, resulting in turn in an increase in the algal population. The disposal of dredged material can be a problem, especially if the sediment contains toxins (EPA 1973). To further complicate the dredging issue, lakes and other bodies of water are often used for disposal of sludge, which can contain very high levels of toxins. Similar problems exist for river and bay dredging as well. Because of the potential problems and the potential for further damage, obtaining permits for dredging can be a long and costly process.

Another method of mitigating sedimentation effects is physically covering the lake sediments. Sheeting material (plastic or rubber) has been used to seal the sediments at the bottom of a lake. Particulate matter (clay or fly ash) is also used to seal the sediments. These methods stop the exchange of nutrients in the sediment with the overlying water. Associated problems include ballooning of the sheeting material, rupturing of a seal, and the migration of gases generated within the sediments. The particulate matter apparently works better than the sheeting material because it effectively seals the sediment. Fly ash, when used as a particulate-matter seal, also removes phosphate from the water column, which can be an added desirable effect (EPA 1973).

Tiered sampling and various sampling methodologies are as stated previously in the stream section.

Current status of research

Classification by trophic level has been extensively studied. Within this area, the focus has been on biologic indicators of trophic status. A study by Manny and others (1989) assesses fish spawning success in response to cultural eutrophication. The preferred trophic status indicator has been benthos, unlike indicators in stream or estuary systems. Problems that arise with benthic indicators are limitations with sampling and sorting of the benthic species. The overall emphasis of research has been on quantification of the eutrophication process (Leach and Herron 1992).

There are limitations to the current feasibility of lake sediment studies. One limitation is freezing. Constant monitoring is impeded in lakes that freeze over during the winter. This applies to a significant portion of the lakes in North America and is a particular problem for the Great Lakes Region, where most lake studies are conducted in this country. Another limitation is water depth. This is easily overcome with diving gear but the real limitation is money and access. When diving gear and divers are required to obtain field data, the cost of the study increases considerably. This is also a limitation for the number of times samples are to be taken and obviously prohibits daily monitoring for many locations. Spawning grounds in the Great Lakes are often 10 to 15 meters below the surface of the lake, so that special equipment is necessary for sampling and monitoring (Manny, Jude, and Eshenroder 1989).

Methods for sedimentation monitoring have become more sophisticated with the technological advances of the past 20 years. Remote sensing (satellite imagery) can be used to monitor surface water color. This provides data about the amount and distribution of fine sediments in larger lakes. This technology is available but is still fairly difficult and expensive to apply (Bukata 1992).

Side-scan sonar is another technological advance which can be applied to sedimentation effects. Systematic mapping of lake beds and identification of potential spawning habitat is feasible with side-scan sonar. Ground truthing with remotely operated submersibles which contain video recorders and camera equipment can be used in conjunction with the side-scan sonar to provide highly accurate mapping capabilities (Edsall 1992). Again, this is a very expensive method and is still in its experimental stage.

Recommendations for future research in lakes and reservoirs

More basic data on lake sedimentation are needed. There has been a strong emphasis on sediment/toxin relationships and the effect on lake habitat, but the actual effects of the sediment have been neglected. A significant amount of work has focused on aquatic insects and sediment (Resh and Rosenberg 1984) and their interaction, but this work does not address the effects of excess fine sediment.

A review by Minshall (1984) strongly supports the need for more research in lake environments and the determination of indicator species. In the field of freshwater benthic invertebrate ecology, the insect/sediment relationship has been intensively studied (Minshall 1984). This knowledge base should be utilized for future studies in aquatic ecosystem dynamics.

Besides more intensive and quantitative studies, improved communication between disciplines is necessary. Often published material is lumped into journals of the particular discipline of the researcher and becomes hidden in the morass of material. This problem is being overcome with databases that list individual articles. Researchers must be willing to look beyond their own fields into related areas where the research has a different perspective. Eliminating repetitive studies will allow for a greater variety of studies. Publication of negative results would be a large step towards reducing duplication.

There is a shortage of long-term, well-monitored projects. This may be the result of funding limitations or time limitations. Theses and dissertations are a large source of information but are limited as to the length of the study period, which also precludes monitoring. An empirical study is greatly strengthened by monitoring before, during, and after the study. The time frame of these studies is dependent on the phenomenon that is being studied, or on the length of academic enrollment.

Evaluation of studies after they are completed provides information about the scientific method and applicability of the techniques employed. This type of evaluation provides information and direction for future studies and allows an objective review of research techniques.

The Estuaries

Estuaries have been studied in depth by numerous disciplines. Biologists are interested in estuaries for their biotic diversity and production. Geophysicists are interested in the fluid/mud dynamics, as are civil engineers who are concerned about navigation channels. The use of estuaries by fish is of concern to fisheries management specialists. Most of this knowledge and interest has been limited to the researcher's own professional peers and has lacked the advantages of interdisciplinary research.

The concern for estuaries is growing, and there is a need for practical, useful data and associated management practices. Estuaries have been recognized for their large biomass production and pollution-filtering systems. The emphasis has been primarily on the flora of estuaries and not the fauna, except for bird uses. Estuaries are important for anadromous fish because it is an passage that they must make when migrating from the streams to the ocean or on their return to spawn. Estuaries also serve as a feeding ground and nursery for many fish and shellfish species. Catadromous fish, such as eels, spawn at sea but spend a large portion of their lives in coastal estuaries. Because of the physical, chemical, and biotic diversity of estuarine systems, they are among the most biologically diverse and richest systems found on earth.

Estuaries are extremely sensitive to human action. Most large bays have associated large estuaries and also have sizable seaport cities associated with them. A majority of the world's population lives along the coast line, so estuaries are significantly impacted by land-use practices, recreation, and exploitation. Ship traffic near estuaries can be especially heavy and affects the entire estuarine ecosystem, because it introduces new variables including physical and chemical alterations.

One of the major estuarine sediment alterations imposed by industrialized societies is dredging. Estuary channels are dredged to keep shipping corridors open. Estuaries are also sites of dredging for sand and gravel for industrial and commercial use. Filling in bays and estuaries for development purposes has been a practice adopted by many coastal cities. The San Francisco Bay is an excellent example of aquatic habitat loss due to filling. Now that the ecologic importance of estuarine environments has been acknowledged, the preservation and restoration of these environments has begun.

Types of estuaries

Estuary classification can be based on a number of parameters. Classification by salinity and by morphology are the two most common approaches.

There are three basic estuary types based on salinity classification: freshwater, brackish, and marine. The freshwater estuaries are dominated by inflow from the rivers, which keeps the salt water pushed out of the estuary. Brackish estuaries exhibit a mixing of salt water and fresh water. Marine estuaries are dominated by tidal action and can have salt levels very close to those of the offshore ocean. Another salinity classification can be made based on relative evaporation rates. If evaporation at the surface of the estuary is less than the river inflow, then it is considered a positive estuary; if evaporation exceeds river inflow, then hypersaline conditions exist and the estuary is considered to be negative. Positive estuaries are by far the most common (Dyer 1973). The relative mixing between fresh water and salt water in each of these types depends on relative salinity and temperature differences between the two sources of water. It is common to have a wedge effect. If two sources of water (one saline, the other fresh) of the same temperature converge, the salt water will wedge beneath the fresh water because the fresh water has a lower density than the salt water. However, if the salt water is warmer, a convection current may form causing vertical mixing. This is referred to as thermohaline convection (Dyer 1973).

A topographic or morphologic approach to classification was introduced by Pritchard (1952). This system also has three basic estuary types: drowned river valley, fjords, and bar-built estuaries. The drowned river valley is a result of the post-Pleistocene marine transgression. The lower portions of stream valleys are flooded due to rising sea level. These estuaries typically are triangular in shape (small at the stream channel, wide at the mouth), and have a small sediment load compared to the stream discharge. These types of estuaries are common in the temperate mid-latitudes and many are found along the west coast of the United States such as San Francisco Bay. Fjords are the result of glaciation and are found in the higher latitudes and in mountainous areas. They typically are rectangular in cross-section and have a low width to depth ratio (10:1). Deposition of sediment in fjords is generally limited to the upper end of the estuary where the stream encounters standing water. Fjords are very common in Scandinavia; the Hardangerfjord in Norway is an excellent example. Bar-built estuaries are similar to drowned river valleys. The major difference is the sediment input into the system and the bar across the mouth of the estuary. A large sediment supply creates shallow lagoons and marshes and helps to maintain the bar. These types of estuaries are found in the tropics and in areas with active coastal deposition (Dyer 1973). Galveston Bay is an example of a Gulf Coast bar-built estuary. For sediment studies, Pritchard's 1952 classification remains the most useful.

Hydraulic and sediment characteristics of estuaries

A characteristic of estuaries is that their beds are constantly moving because of river inflow and tidal fluctuations. The bedload is composed mainly of sand-sized particles which are easily entrained and move for long distances. The bed material is not always transported in a downstream direction. Depending on tidal influences, material may be moved up and down the channel. Fine silts and clays flocculate in the salt water and are deposited in tidal marshes.

The dynamics of sediment transport in and through estuaries is extremely complex. Many studies have been done in the field of geophysics to gain an understanding of the transport processes. The equations and theories derived from fluvial studies are not directly applicable (if at all) to the estuarine environment. The complicating factors include diurnal and biweekly tidal cycles, salinity influences, temperature differences, and fine-sediment transport. When clays encounter saline water their electrical charges are affected and the clay will flocculate and form larger particles. Thus, when the sediment settling velocity is determined using Stoke's Law (an equation used to calculate settling velocity of different-sized particles), the actual settling velocity may be much higher.

A study of the sediment delivery to Atlantic estuaries of the United States by Phillips (1991) focused on the bedload transport through these systems. The relative effects of land-use practices or changes were evaluated on the basis of soil erosion and the possible effect that this would have on downstream estuaries. This study did not rely on complex equations to model sediment transport but rather focused on sediment yield and sediment delivery ratios.

Phillips (1991) found that estuarine sediment is derived from fluvial sediment input, shoreline erosion, and migration of marine sediments inland. Fluvial sediment inputs were the dominant process affecting these estuaries. Of the estuaries studied, a fluvial sediment delivery ratio of 4 percent was derived: that is, only 4 percent of the sediment eroded from the uplands and delivered to the stream ever makes it to the estuary. If this is occurring then a huge amount of sediment is being stored in and along these stream channels. Phillips (1991) also indicates that sediment storage is much more environmentally sensitive than basin sediment yield and concludes that dramatic changes in the watershed would be required to alter the sediment budget in the estuary. However, processes that mobilize stored sediment would have a large effect on the sediment budget. Another important statistic discussed by Phillips (1991) is the storage capacity of the estuaries. He believes that 90 to 95 percent of all coastal sediment storage occurs in estuaries and coastal wetlands and that up to 95 percent of watershed-derived sediment is stored in the basin.

This has interesting implications for management. Even though sediment delivery may be low, total sediment input can be high. Stopping sediment before it reaches the stream channel is important because once it becomes stored in the channel it can be easily remobilized. Efforts to reduce sedimentation rates will be long-term because large quantities of sediment are already in stream channels due to agricultural and land-use practices of the early twentieth century. If sediment is in long-term storage in estuaries, rather than en route to the continental shelf, then sedimentation rates should be of great importance.

Increased fluvial sediment in estuaries may result in extended tidal marshes, shoaling, infilling of navigation channels, reduction of benthic and aquatic habitat, and reduced primary productivity due to turbulence and limited light penetration (Phillips 1991).

Another sediment transport study by Horne and Patton (1989) came up with conflicting results. They found that the trapping mechanism in an east coast stream was inefficient and that "partially mixed estuaries on microtidal coastlines may in fact be effective conduits of bedload sediment onto the continental shelf" (Horne and Patton

1989). They also stated that there are not sufficient data available on river inflow into estuaries to explain this disparity completely.

Aquatic habitat characteristics

Estuaries are utilized by specialized organisms that have adapted to fine sediments, high sedimentation rates, and mobile substrate. The macroinvertebrates that are found in the substrate of estuaries are much smaller than those found in streambeds with larger particle sizes. Common benthic organisms found in estuaries tend to be opportunistic rather than an equilibrium type of species (Schaffner et al. 1987). Within the estuary, the density of fauna is commonly greater in the freshwater tidal areas than in other parts of the estuary (Schaffner et al. 1987). The species diversity of macroinvertebrates is usually lower in fine-sediment substrates than that in coarser-particle substrates. The diversity and evenness of species decline with an increasing percentage of silt/clay and organic matter (Junoy and Vieitez 1990). However, fine-sediment beds are important for burrowing tube-making invertebrates and other burrowing species (Minshall 1984).

Sediment quality of estuaries

Sediment quality is very important in estuaries because of the residence time of the sediment. A study by Cunningham and others (1987) addressed the issue of sediment in estuaries and the interaction with pesticides. The pesticide that they were interested in was diflubenzuron or DFB. This chemical is commonly used as a larvicide to control mosquitoes. This product has not, however, been approved for use in salt marshes. DFB interferes with chitin formation, which would negatively affect crustaceans when they molt. The study by Cunningham and others (1987) focused on two crustaceans: brachyuran crabs and caridean shrimp. There were two test groups and a control group of these crustaceans. Two environments had the same levels of DFB, but one contained sediment while the other did not. After 22 days, the environment with sediment contained only 5 percent of the original DFB in the water column and survival of that test group compared with the control group was good. The environment without sediment still had high levels of DFB and there was no survival of the crustaceans (Cunningham et al. 1987). This indicates the important chemical bonding that occurs between biocides and fine sediments, but the biocides remain stored in the estuary sediment and do not disappear. Cunningham and others (1987) warn that the DFB in the sediment may affect juvenile and adult crustaceans because they feed on detritus and organic matter found on the bottom of estuaries.

Similar sediment quality issues exist for all chemicals that enter estuaries and are bound to sediment. The sediment is stored on the bottom of the estuary until it is disturbed by natural processes or human activities. The impacts of dredging become a critical issue when sediments are the storage facility for industrial and agricultural chemicals.

Tiered sampling and various sampling methodologies are as stated previously in the stream section.

Current status of research

Estuaries have recently obtained national recognition. Many estuaries are now being studied and evaluated for restoration efforts. Tillamook Bay in northwestern Oregon is one such estuary that is now part of the National Estuarine Program (NEP). Pollution caused by agricultural runoff is a major concern for many estuaries in the United States. What once was considered "useless" land is now being utilized for its filtering and cleansing effects. The estuary at Arcata, California, was rehabilitated and enhanced for wildlife habitat, for recreational use, and for tertiary sewage treatment, which performs a final filtering of sewage water before it enters the ocean. This system has been very successful and is being duplicated in many other areas, not only in estuaries but also in interior wetlands.

The study of estuaries has been emphasized in the United States, the Netherlands, Australia, Germany, Denmark, France, and South Africa. Most of the work has dealt with estuarine biotas, but significant work has been done on the physical environment. Much of the work being done is to supplement or test computer models. Estuaries are such complex systems that modeling was not really feasible without computers. Modeling requires diverse information about a system if it is to be truly representative of the system. This encourages and almost mandates interdisciplinary work.

Recommendations for future research in estuaries

Basic research and baseline data are needed for estuaries. Long-term monitoring and evaluation should be set up to provide as much base information as possible. Since this is one of the richest and most sensitive aquatic environments, the concern for estuaries will probably continue to expand during the next several decades. Restoration efforts and municipal interests (such as tertiary sewage treatment) will require more information and data about estuaries and their dynamics.

Emphasis should be placed on interdisciplinary studies. The Panel on Estuarine Research Perspectives (1983) recommended that "the primary focus of future research in estuaries should be on interdisciplinary relationships." They also recommended that government and universities provide data and the basic framework for informed estuary management. The interdisciplinary research is beginning to happen in estuarine studies as it is in many other ecosystem-based studies. Much of the government data about estuaries is provided by the Environmental Protection Agency. Universities are providing a large source of data about estuaries especially those estuaries which are a part of the National Estuarine Program. A comprehensive approach that examines interactions of physical, geologic, chemical, and biologic components is desperately needed in this field of study, and if the current trend continues this need may be met within the next few decades (PERP 1983).

According to Junoy and Vieitez (1990), soft-bottom macrozoobenthos has been relatively neglected by benthic researchers. This is a very important area in estuary sedimentation evaluations, especially if an indicator species is a necessary part of the evaluation. The lack of data about sediment transport into estuaries from rivers makes it extremely difficult to develop an accurate sediment budget for estuaries (Horne and Patton 1989). Sediment budgets are necessary for long-term planning in coastal areas. Sedimentation in the fluvial/estuarine interface is another area that requires more in-depth research. This area is very sensitive to disturbance because of the change in gradient and the sediment storage that occurs at this transition (Phillips 1991). Mobilization of this stored sediment can have a dramatic impact on the quality of the estuary.

Influence of Land Use

The effects of land use are apparent across the spectrum of problems associated with aquatic environments. Increased erosion and acceleration of sediment transport can frequently be related to land-use changes or to poor land management. Effective land management or watershed management can lead to a reduction in the amount of sediment delivered to a stream channel. Prevention of erosion is a first step; if erosion occurs, keeping the sediment on the hillslopes is a second step; if the sediment is delivered to the stream channel, estuary, or lake, then the third step is restoration of the aquatic environment. Land use can be broken down into six broad categories: forest, range, agriculture, industrial, urban, and water resources.

Forestry

The work in forestry applications and effects has been intensely studied. There are many excellent papers that discuss forest management and the impacts of harvesting activities. One interesting finding is that the logging roads, not the harvesting practice itself (unless both sides of a streambank were clear-cut), are responsible for a large percentage of the sediment that enters an aquatic environment at an accelerated rate (Everest et al. 1987). In effect, the channel network is increased because the roads act as tributaries, creating a more efficient sediment delivery system. Sediment that was once far from the stream channel is now transported through a series of inboard ditches and culverts directly to the stream. Practices that keep sediment out of the stream, such as stream buffers, are not sufficient when a significant road network is in place. Sediment must also be kept off of the roads, which are essentially part of the stream system. Erosion of cut banks and fill slopes is a severe problem where culverts are in place. The concentrated flow can easily erode a fill slope if the culvert is not properly sized or placed.

Another impact of forest roads is the direct interface with riparian vegetation. In areas where stream crossings are required, riparian vegetation is removed. The removal of vegetation destabilizes the banks and may result in bank erosion. If proper mitigation techniques are used (revegetation efforts), the loss of riparian vegetation should only be temporary.

Timber harvest practices, such as clear-cutting and selective cutting, have a direct impact on sedimentation rates in a stream system. When vegetation is removed, soils are destabilized because of slope characteristics, loss of moisture, loss of canopy cover, and loss of root strength. The sediment is mobilized during storm events and is moved initially by sheet & rill erosion or gully erosion. Other sediment transport occurs as debris flows or landslides. Proper timber harvesting techniques can minimize the mobilization of sediment.

Many current state and federal forestry regulations minimize or prohibit timber harvesting in riparian zones. This provides a buffer strip between harvested land and streams. By quantifying the physical parameters of the riparian buffer zone, a truly protective buffer width can be determined. Phillips (1989) has proposed a model including soil type, geomorphic features, and vegetative complexes, to determine the necessary width of a riparian buffer which would adequately filter sediment and nutrients and protect the stream. Myers and Swanson (1992) have found that stream stability and resilience are closely tied to stream type. They utilized Rosgen's 1985 stream classification system to generalize stream stability and resilience. Using these tools, forestry managers can more adequately determine the width of riparian buffer zones to allow maximum harvesting potential while concurrently protecting a stream system.

Range

Research in the area of rangeland impacts has been significantly less than that of forestry. Nevertheless, grazing on rangeland has serious implications for the increased sediment supply moving into aquatic systems. Compaction of the soil by grazing animals along with a reduction in ground cover causes increased runoff and less infiltration into the soil. The increased runoff causes the hydrograph to become steeper with higher peak flows. This excess energy may be expended in incision of the stream channel or erosion of the stream banks.

Direct effects of the grazing animals are also important to recognize. If the animals have no source of water, such as a watering trough, they will migrate towards rivers and lakes, trampling down vegetation and destabilizing banks. Livestock spend more time in riparian areas than in upland areas; consequently the riparian areas are more intensively grazed (Armour et al. 1991). Besides the direct impact on streams and lakes from trampling, there are secondary effects as well. Increased turbidity from erosion of the banks reduces primary productivity in the stream, in turn reducing the available food in the stream and adversely affecting the fish habitat. The destabilized banks may cause the channel to become wider and shallower (CIEATFWH 1982). Once the channel becomes wider and shallower it may continue to meander within the banks and increase bank erosion, causing an increase in the sediment supply and a decrease in the stream's ability to move all of the sediment in the channel.

Fencing off riparian zones for protection from grazing cattle has proven to be very successful. Recovery rates are generally rapid (within 5 years) and the cost is relatively low. Other alternatives to total livestock exclusion include light grazing levels, late-season grazing, and rest-rotation grazing systems (Sedgwick and Knopf 1991). Sedgwick and Knopf (1991) found that year-long and spring-summer grazing were especially damaging to range quality. They also found that two factors, initial grazing at proper levels and late-year grazing, were most responsible for range resilience. Late-year grazing is important in the western United States because it is the dormant season for most range plants and it is also a period of low rainfall and low stream discharge (Sedgwick and Knopf 1991).

A position statement by the American Fisheries Society (Armour et al. 1991) states, "The riparian problem is further complicated because today's range management guidelines do not call for different management strategies for upland and riparian vegetative types. Because riparian environments are lumped into broad terrestrial environmental classifications, they become unidentifiable for land-management purposes." The authors believe that the primary effect of grazing on aquatic systems is the addition of fine sediment from bank erosion and upland soil erosion. The American Fisheries Society supports livestock management that includes the protection and recognition of riparian zones (Armour et al. 1991).

Agriculture

If the trend in agriculture is towards increased production, utilization of marginal lands for crop production could cause increases in erosion and sedimentation. This is a major concern for marginal lands that are currently under the Conservation Reserve Program (CRP) and will presumably return to agricultural production when their owners' contracts expire. However, producers will be required to place their land into acceptable conservation systems to retain USDA support. The future conversion of rangeland and woodlands will be controlled by the Sodbuster provisions of the Food Security Act of 1985, but any conversion to crop production will require increased use of agricultural chemicals to attain acceptable yields. Marginal lands are typically more erodible because of steeper slopes (CIEATFWH 1982).

The loss of small farms to large industrial farms may also lead to erosion problems. Fencerows are eliminated as single properties become larger. These fencerows act as a buffer strip and can trap sediment. Because of increasing demands for agricultural products, crop rotation may become less frequent and double cropping will become more frequent (CIEATFWH 1982).

The arid West is limited in the amount of land that can be converted to cropland because of water and energy limitations. Drip irrigation should lead to a reduction in sediment and nutrient transport to local water systems as well as to increased water efficiency. The regions east of the Mississippi still have potential for further agricultural development: productivity could be greatly increased by the use of double cropping and irrigation. That would lead to greater erosion and runoff (CIEATFWH 1982).

The primary effect of agriculture is agricultural runoff. Runoff may simply cause erosion of the topsoil, but it may also transport agricultural chemicals that are bound to the particles being eroded. The concern for agricultural runoff is not only excess sediment, but also the potential for the introduction of toxins into an aquatic system. Significant technology exists to prevent agricultural erosion and runoff but it is often expensive and underutilized. Debris basins, settling ponds, and other structures can be used to catch sediment and clarify water before it enters a hydrologic system. However, keeping the soil on the field makes the most ecologic and financial sense.

In areas where surface water is unavailable because of prior allocation or seasonal fluctuations, ground water is utilized. If the ground water is heavily used, local lowering of the water table may occur. This can result in the death of riparian vegetation, which may rely on shallow ground water for the dry seasons of the year. Death of the riparian vegetation causes destabilization and erosion of streambanks and the riparian buffer is eliminated. Lowering of the water table may also result in the lowering of a nearby, hydrologically connected lake or reservoir.

Another impact of past agricultural practices was the removal of riparian vegetation to increase arable lands. Floodplain soils commonly are very fertile, productive, and relatively level. Those qualities combined with proximity to water all promote conversion to cropland. Because of the proximity to water, sediment delivery tends to be high (i.e. >60 percent). There is considerable public interest in restoring streams and riparian areas, so there may be some reversal of the recent losses.

The riparian buffer strip is important because it acts as a filter between the agricultural land, or any other land use, and the stream. If this buffer is removed to increase cropland or dies because of dewatering of the local aquifer, sediment has a more direct path to the stream channel. A study by Lowrance and others (1984) found that riparian forests in agricultural watersheds play an important role in nutrient and sediment filtering. These riparian forests are usually not managed because the soils tend to be poorly drained and require a considerable initial economic investment to bring them into cultivation. The potential benefits of riparian forests in agricultural watersheds should be investigated and maximized in designs for water-shed management (Lowrance et al. 1984).

Industrial

Industrial uses include large manufacturing companies, open pit mining, sewage treatment plants, and many other consumptive industries. Mining was the focus of many papers in the first half of this century. Mining spoil was allowed to enter lakes and fluvial systems with very little regulation. Because this was generally point-source pollution with sometimes devastating effects, legislation was passed to prevent severe environmental degradation due to mining operations. The motive of such laws was not always or even primarily environmental concern; for example, the prohibition of hydraulic mining was implemented on economic grounds because it was destroying agricultural lands.

Several papers have dealt with the effects of industrial sediment pollution. This work has been carried out primarily in the eastern United States as a result of heavy industry along many of the eastern rivers and in the Great Lakes region. An example is a study by Alexander and Hansen (1977), which addresses the effects of sediment from a gas-oil well drilling accident in Michigan. This study focuses on high-level, instantaneous industrial pollution. Low-level industrial pollution occurring over the span of years or decades is also extremely important. This type of pollution does not easily lend itself to single studies which are limited temporally. Low-level pollution requires years of monitoring to establish trends of toxin migration, uptake, and deposition. More long-term studies of low-level industrial pollution are needed.

The effects of mining include not only an increase in sediment but also an introduction of toxins. These toxins, very often heavy metals, are bound to the sediment which is eroded and washed into the hydrologic system.

Urban

Urban sediment pollution usually consists of temporary sediment pulses associated with construction of buildings and roads. However, longer-term stream and streambank erosion problems do occur because of floodplain and channel filling. Channel constriction causes an increase in tractive stress (boundary shear stress), which may lead to erosion and sedimentation problems.

There has been a large push to limit the amount of runoff that moves directly into a fluvial system from urban land use, but much remains to be done. Increased runoff because of decreased infiltration rates has the same effect as overgrazing. The peak flows are increased, which increases velocities and causes incision and erosion of the stream channel. Again, most sediment moving from urban areas moves from point sources, such as drainage ditches. A practice that is being utilized for urban storm drain mitigation is detention ponds. These are often incorporated into the landscape as scenic open areas while serving an important hydrologic purpose.

New engineering technology and protective measures have greatly reduced the amount of erosion that occurs during the construction phase of a development project. In addition, many units of government have passed urban erosion control ordinances to address urban erosion problems.

Water Resources

Among the largest impacts on sedimentation and the associated effects in aquatic systems are those caused by instream structures designed for water storage, diversion, and flood control. Dams are one of the most severe alterations to a stream. Bedload transport is stopped and peak flows are reduced. The reduction in peak flow quantity and intensity results in a reduced capacity to carry sediment. The flushing effect of large storm events is essentially halted. All this can result in a buildup of tributary sediment in the channel over many seasons, rather than a dry-season buildup with periodic flushing. Downstream scour as a result of long-duration clean water releases from dams is also a problem because there is high sediment recruitment directly below the dams. Stream diversions for agricultural water or hydroelectric generation also diminish the stream's capacity for sediment transport. The reduced tractive stress results in aggradation of sediment in the stream channel.

Conservation Management Systems

The best way to reduce all sedimentation effects (Table 1) is to plan conservation management systems throughout whole watersheds. NRCS in future will plan for the soil, water, air, plant, and animal resources and their interrelationships. The agencies can no longer provide alternatives and assistance that address individual problems like sheet & rill erosion without taking the effects on all five natural resources into account. Our involvement with water quality has brought this "reality" concern to the surface, as has the public's growing concern for the environment, especially wetland protection, food and water safety, fish and wildlife protection and enhancement, and a sustainable agriculture. Therefore, the effects of sediment (displayed in Table 1) need to be addressed in planning, with one focus being the effects of sediment on aquatic habitats.

As a technical agency, NRCS must constantly strive to improve methods to evaluate the potential effects of conservation practices on the natural resources when providing technical assistance. It is necessary to determine the physical effects relevant to each resource during the planning process because a conservation practice which has a positive effect on one resource may have positive or negative effects on other resources. One conservation practice usually does not completely solve a problem because consideration must be given to all five resources (soil, water, air, plants, and animals) and to the human factor.

Conservation Management Systems (CMS) are used to identify the two levels of soil, water, air, plant, and animal resource conservation that can be achieved through NRCS assistance to clients with planning and application. These two levels of treatment are Resource Management Systems (RMS) and Acceptable Management Systems (AMS). The quality criteria for both RMS and AMS are in Section III of the NRCS Field Office Technical Guide (FOTG).

Natural resource planning assistance will be directed toward development and implementation of Resource Management Systems (RMS). An RMS is defined as a combination of practices for land or water used within their capabilities that, as planned, will at a minimum meet established quality levels, and when installed, will provide for the conservation, protection, and/or improvement of the resource base for soil, water, air, plant, and animal resources. An RMS can be developed for any conservation treatment unit, depending on the needs and desires of the decisionmaker; however, one RMS will seldom suffice for an entire planning unit. When the RMS concept is applied on a watershed-wide basis, then all of the interactions and cumulative effects can be considered, and effects such as sediment reduction can be addressed in an ecosystem context.

To date, Resource Management Systems have been applied on more than 587 million acres throughout the United States. In fiscal year 1994, RMS were applied on 17.5 million acres. The 1994 application occurred when there was still a heavy NRCS program emphasis on sheet & rill erosion under the Food Security Act (FSA) of 1985 and the Food, Agriculture, Conservation and Trade Act (FACTA) of 1990. In addressing just sheet & rill erosion on highly erodible cropland, the NRCS in fiscal year 1994 provided assistance to treat more than 3.5 million acres, thus reducing average sheet & rill erosion on those acres from 17.7 tons per acre to 5.9 tons per acre, a decrease of 67 percent.

The impacts of the Food Security Act of 1985 on the area above the Lower Granite Reservoir in Oregon were addressed by Reckendorf and Pedone (1989). They determined that 820,416 acres of dry cropland in that area were eroding at an average rate of 17 million tons per year. By retiring highly erodible land and putting conservation systems into effect, an 85 percent rate of landowner participation would result in a 67-percent reduction in annual erosion on dry cropland (from 21.5 tons per acre to 7.1 tons per acre). This would further result in a 42 percent reduction of sediment yield (959,460 tons) into the Lower Granite Reservoir.

It is difficult to project the effect of this sediment yield reduction on the aquatic habitat along the rivers leading to the reservoir. However, a study by McNamee (1985) along Mission Creek, which is a tributary of the Lower Granite Reservoir, projected that there would be an average annual benefit to the steelhead fishery from erosion control and sediment reduction of $0.41 per ton of sediment.

Not all of the sediment yield from the highly erodible land that was treated may have reached streams to impact aquatic habitat. However, the treated sheet & rill erosion areas, particularly those converted to grasslands under the Conservation Reserve Program of FSA, would reduce erosion of the finer particles (clay, silt, and fine sand) that have a higher sediment delivery ratio to reach streams and impact aquatic habitat.

In resource areas where social, cultural, or economic characteristics make it infeasible to implement a Resource Management System, planning to the Acceptable Management System level may apply. An Acceptable Management System is designed to treat soil, water, air, plant, and animal resources at a level which is achievable in view of the social, cultural, and economic characteristics of the resource involved.

Rarely does conservation planning result in an RMS that is quickly applied. Much of the time a customer's decisions to treat resource problems are reached progressively over time. This progressive planning (consultative selling in private industry) is the incremental process of building a plan on part or all of the planning unit consistent with the decision maker's ability to introduce improvements over a period of time. Even though the planning and decision making may be done progressively, it will always be directed toward the planning and ultimate implementation of a Resource Management System.

Concluding Remarks

The emphasis of this paper is on sediment and its effects on the aquatic environment. This has become a very important issue in the United States and other countries because of expanding urban centers, greater use of natural resources, and the expansion of agriculture onto marginal lands. The more intensively the land is used, the greater is the potential for erosion and sedimentation problems. Erosion and sedimentation can adversely effect aquatic habitat and the species that depend on it. It will become imperative for land-use managers and natural resource planners to recognize, emphasize and mitigate erosion and sedimentation problems.

Streams, lakes, and estuaries are all susceptible to sedimentation and erosion problems. Each system responds in a different way to accelerated sedimentation, so each system should be evaluated independently of the others, recognizing that hydrologically these systems may be closely connected.

Not all streams respond to sedimentation in the same way. Depending on the stream character (gradient, sediment transport, discharge), accelerated erosion and sedimentation will have varying effects. By knowing the basic characteristics of certain types of streams through a classification system, some generalizations and predictions can be made about channel response. This does not replace a thorough stream investigation but it provides information for planning purposes.

Lake sedimentation requires a different method of evaluation because treating the watershed problem may not be enough. Lakes do not flush their systems of fine sediment, so sediment removal may be required to restore aquatic habitat. For this reason lakes are much more sensitive to sedimentation than are streams. Estuary sedimentation is very complex because sediment transport is not always unidirectional. Tidal fluxes and stream fluxes are combined, making sediment yield estimates very difficult, and effects along shorelines are as important as effects in the watershed. Flocculation and significant human influences. can further aggravate the problems.

These three systems (streams, lakes, and estuaries) seem to be very different, yet they are all part of a larger, even more complex ecosystem. The interrelationship must be recognized and addressed when planning any type of basin or watershed projects.

Environmental sensitivity and environmental activism are on the rise and the result will be increasing demand for a cleaner, healthier environment. This healthier environment must be balanced with an ever increasing need for forest products, agricultural products, and rangeland for cattle. Keeping sediment on the watershed, whether it be forest, range, agricultural, industrial, or urban lands, makes economic and ecological sense. For NRCS, the best opportunities to reduce sediment's effects come when planning with individuals, groups, and units of government. The importance of ecosystem-based assistance must be emphasized in planning conservation management systems that integrate the effects on soil, water, air, plants, animals, the land user, and the community. The greatest reduction of sediment impacts on aquatic habitat will occur when conservation management systems are planned and installed on a whole-watershed basis.

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